

FREQUENCY-INDEPENDENT SPATIAL PROCESSING FOR WIDEBAND MISO AND MIMO SYSTEMS

BACKGROUND

I. Field

[0001] The present invention relates generally to data communication, and more specifically to techniques for performing spatial processing for wideband multiple-input single-output (MISO) and multiple-input multiple-output (MIMO) communication systems.

II. Background

[0002] A MIMO system employs multiple (N_T) transmit antennas and multiple (N_R) receive antennas for data transmission and is denoted as an (N_T, N_R) system. A MIMO channel formed by the N_T transmit and N_R receive antennas may be decomposed into N_S independent channels, where $N_S \leq \min \{N_T, N_R\}$. N_S spatial channels may be formed by the N_S independent channels of the MIMO channel and used for data transmission.

[0003] For a time dispersive MIMO channel, a signal sent from a given transmit antenna may reach a given receive antenna via multiple signal paths (i.e., propagation paths). These signal paths may include a line-of-sight path and/or reflected paths, which are created when the transmitted signal reflects off reflection sources (e.g., buildings, obstructions, and so on) and arrives at the receive antenna via different signal paths than the line-of-sight path. The received signal at the receive antenna may thus include multiple instances (i.e., multipath components) of the signal sent from the transmit antenna. The delay spread L of the MIMO channel is the time difference between the earliest and latest arriving multipath components (of some certain minimum energy) for all of the transmit-receive antenna pairs in the MIMO channel.

[0004] Time dispersion in the MIMO channel causes frequency selective fading, which is characterized by a frequency response that varies across the system bandwidth (i.e., different channel gains for different frequencies). The multipath components are associated with different complex channel gains and may add constructively or destructively at the receiver. Time dispersion and frequency selective fading are more problematic for a wideband MIMO system with a wide system bandwidth.

- [0005] Various techniques may be used to combat frequency selectivity in a wideband MIMO channel. For example, a multi-carrier modulation technique such as orthogonal frequency division multiplexing (OFDM) may be used to partition the system bandwidth into multiple (N_F) orthogonal frequency subbands. The wideband MIMO channel may then be viewed as being composed of N_F flat-fading narrowband MIMO channels, each of which may be decomposed into N_S spatial channels. Data may then be transmitted on the N_S spatial channels of each of the N_F subbands.
- [0006] For a MIMO system that utilizes OFDM (i.e., a MIMO-OFDM system), the wideband MIMO channel can be characterized with (1) a complex channel gain for each of the N_F subbands of each of the $N_T \cdot N_R$ transmit/receive antenna pairs (i.e., $N_F \cdot N_T \cdot N_R$ channel gains in all) and (2) the noise floor at the receiver. The channel gains and receiver noise floor may then be used to select the data rate(s) for data transmission on the N_S spatial channels of each of the N_F subbands. The channel gains may also be used for spatial processing at the receiver and possibly the transmitter in order to transmit data on the N_S spatial channels of each of the N_F subbands. Thus, for the MIMO-OFDM system, frequency selectivity can be combated by treating the wideband MIMO channel as N_F flat-fading narrowband MIMO channels and performing spatial processing separately for each of the narrowband MIMO channels. However, this frequency-dependent spatial processing can greatly increase computation complexity at the transmitter and receiver. Moreover, the receiver may need to provide a large amount of feedback information (e.g., the channel gains) to the transmitter to support frequency-dependent spatial processing.
- [0007] There is therefore a need in the art for techniques to more efficiently perform spatial processing in a wideband MIMO system.

SUMMARY

- [0008] Techniques for performing frequency-independent eigensteering in MISO and MIMO systems are provided herein. Eigensteering refers to spatial processing performed on a data symbol stream with a steering vector at a transmitter in order to transmit the data symbol stream on a spatial channel of a MISO channel or a MIMO channel. The MISO channel may be characterized by either (1) a sequence of time-

domain channel impulse response vectors for a plurality of time delays or (2) a sequence of frequency-domain channel frequency response vectors for the N_F subbands. Similarly, the MIMO channel may be characterized by either a sequence of channel impulse response matrices or a sequence of channel frequency response matrices. The eigensteering is frequency-independent in that one steering vector is used for the data symbol stream even if the MISO or MIMO channel is time dispersive and regardless of whether the eigensteering is performed in the time domain or the frequency domain. Eigensteering may be performed on one or multiple data symbol streams with one or multiple steering vectors to transmit the data symbol stream(s) on one or multiple spatial channels. Various frequency-independent eigensteering schemes are described herein including principal mode eigensteering, multi-mode eigensteering, main path eigensteering, and receiver eigensteering.

[0009] For principal mode and multi-mode eigensteering, a correlation matrix is computed for the MIMO channel based on the channel (impulse or frequency) response matrices for the MIMO channel, as described below. The correlation matrix is then decomposed (e.g., using eigenvalue decomposition) to obtain N_S frequency-independent steering vectors for N_S spatial channels of the MIMO channel. For principal mode eigensteering, one data symbol stream is transmitted on the principal or best spatial channel using the steering vector \underline{v}_{pm} for the best spatial channel. For multi-mode eigensteering, N_D data symbol streams are transmitted on the N_D best spatial channels using N_D steering vectors \underline{V}_{mm} for these spatial channels, where $N_S \geq N_D > 1$ in this case.

[0010] For main path eigensteering, a data symbol stream is transmitted on the principal spatial channel for the main propagation path of the MIMO channel using a frequency-independent steering vector \underline{v}_{mp} . For this scheme, the energy of each channel impulse response matrix is first determined. The main path is the time delay of the channel impulse response matrix with the highest energy. A correlation matrix of the channel impulse response matrix with the highest energy is computed and decomposed to obtain the steering vector \underline{v}_{mp} for the best spatial channel of the main path. The data symbol stream is transmitted on this spatial channel using the steering vector \underline{v}_{mp} .

[0011] For receiver eigensteering, a data symbol stream is steered toward an individual receive antenna based on a frequency-independent steering vector $\underline{\mathbf{v}}_{rx,i}$ obtained for that receive antenna. The MIMO channel may be viewed as being composed of N_R MISO channels for the N_R receive antennas. A correlation matrix may be computed for each MISO channel based on its sequence of channel (impulse or frequency) response vectors and decomposed to obtain a steering vector for the main spatial channel of that MISO channel. N_R frequency-independent steering vectors $\underline{\mathbf{V}}_{rx}$ may be obtained for the N_R MISO channels. N_D data symbol streams may be transmitted using the N_R steering vectors $\underline{\mathbf{V}}_{rx}$, where $\min\{N_R, N_T\} \geq N_D \geq 1$ in this case. Each data symbol stream may be steered to one, multiple, or all receive antennas. For a MISO system with one receive antenna, one steering vector is obtained for the single receive antenna and used to transmit one data symbol stream.

[0012] For all of the eigensteering schemes, a matched filter is derived for each receive antenna based on the steering vector(s) used by the transmitter and the sequence of channel (impulse or frequency) response vectors for the receive antenna. The received symbol stream for each receive antenna is filtered with the matched filter for that receive antenna to obtain one or more filtered symbol substreams. The filtered symbol substreams from all N_R matched filters for the N_R receive antennas are then combined to obtain N_D detected symbol streams for the N_D data streams sent by the transmitter, where $N_D \geq 1$ in this case. Equalization and other post-processing may be performed on the N_D detected symbol streams to obtain N_D recovered symbol streams, which are estimates of the N_D data symbol streams sent by the transmitter.

[0013] Various aspects and embodiments of the invention are described in further detail below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The features and nature of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

[0015] FIG. 1 shows a transmitter and a receiver in a MISO system;

[0016] FIG. 2 shows a transmit (TX) data processor in the MISO system;

- [0017] FIGS. 3A, 3B, and 3C show three embodiments of a TX spatial processor in the MISO system;
- [0018] FIGS. 4A, 4B, and 4C show three embodiments of a receive (RX) spatial processor in the MISO system;
- [0019] FIG. 5 shows a block diagram of the receiver in the MISO system;
- [0020] FIG. 6 shows a transmitter and a receiver in a MIMO system;
- [0021] FIG. 7 shows a TX data processor in the MIMO system;
- [0022] FIGS. 8A, 8B, and 8C show three embodiments of a TX spatial processor in the MIMO system;
- [0023] FIGS. 9A through 9F show six embodiments of an RX spatial processor in the MIMO system;
- [0024] FIG. 10 shows a block diagram of the receiver in the MIMO system;
- [0025] FIG. 11 shows a process for performing principal mode eigensteering, multi-mode eigensteering, and main path eigensteering in the MIMO system; and
- [0026] FIG. 12 shows a process for performing receiver eigensteering in the MISO or MIMO system.

DETAILED DESCRIPTION

- [0027] The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment or design described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments or designs.
- [0028] The eigensteering techniques described herein may be used for various wireless communication systems including single-carrier and multi-carrier MISO and MIMO systems. Multiple carriers may be provided by OFDM or some other multiple-carrier modulation technique or construct. In the description below, the term “MIMO system” generically refers to both single-carrier and multi-carrier MIMO systems.
- [0029] For clarity, the following notations are used for the description below. Time-domain variables are functions of n and are denoted with cursive texts (e.g., $h(n)$). Frequency-domain variables are functions of k and are denoted with plain texts (e.g., $h(k)$). Vectors are denoted with lower-case bold-faced and underlined texts (e.g., $\underline{h}(n)$ and $\underline{h}(k)$). Matrices are denoted with upper-case bold-faced and underlined texts (e.g.,

$\underline{\underline{\mathcal{H}}}(n)$ and $\underline{\underline{\mathbf{H}}}(k)$). Three-dimension matrices are denoted with upper-case bold-faced and doubly underlined texts (e.g., $\underline{\underline{\mathcal{H}}}$ and $\underline{\underline{\mathbf{H}}}$).

1. MISO System

[0030] A time-dispersive MISO channel with N_T transmit antennas and a single receive antenna may be characterized by a time-domain channel impulse response matrix $\underline{\underline{\mathcal{H}}}$ with dimensions of $(L+1) \times N_T$, where L denotes the delay extent of the MISO channel in symbol periods. The delay extent of a channel is the difference between the earliest and latest resolvable propagation paths in the channel. The matrix $\underline{\underline{\mathcal{H}}}$ is composed of N_T channel impulse response vectors \underline{h}_j , for $j=1, 2, \dots, N_T$, or equivalently, $L+1$ row vectors $\underline{h}(n)$, for $n=0, 1, \dots, L$, which may be expressed as:

$$\underline{\underline{\mathcal{H}}} = \begin{bmatrix} \underline{h}(0) \\ \underline{h}(1) \\ \vdots \\ \underline{h}(L) \end{bmatrix} = \begin{bmatrix} h_1(0) & h_2(0) & \cdots & h_{N_T}(0) \\ h_1(1) & h_2(1) & \cdots & h_{N_T}(1) \\ \vdots & \vdots & \ddots & \vdots \\ h_1(L) & h_2(L) & \cdots & h_{N_T}(L) \end{bmatrix} = [\underline{h}_1 \ \underline{h}_2 \ \cdots \ \underline{h}_{N_T}] , \quad \text{Eq (1)}$$

where entry $h_j(n)$, for $j=1, 2, \dots, N_T$ and $n=0, 1, \dots, L$, is the coupling (i.e., complex gain) between transmit antenna j and the receive antenna for time delay n . Each vector \underline{h}_j , for $j=1, 2, \dots, N_T$, includes $L+1$ complex values for the channel impulse response between transmit antenna j and the receive antenna. Each row vector $\underline{h}(n)$, for $n=0, 1, \dots, L$, includes N_T complex values for the channel gains between the N_T transmit antennas and the receive antenna for time delay n .

[0031] The channel impulse response may be estimated by the receiver based on pilot symbols sent by the transmitter. The transmitter can “cover” the pilot for each transmit antenna with a unique orthogonal sequence assigned to that antenna. Covering is a process whereby a given modulation symbol p (or a set of W symbols having the same value) to be transmitted is multiplied by all W chips of a W -chip orthogonal sequence to obtain W covered symbols, which are then transmitted. N_T orthogonal pilots can be obtained with N_T orthogonal sequences for the N_T transmit antennas. The covering achieves orthogonality among the N_T pilots sent from the N_T transmit antennas and allows the receiver to distinguish the individual transmit antennas.

[0032] The receiver can “discover” the received pilot symbols with each of the same N_T orthogonal sequences to estimate the channel impulse response between each of the N_T transmit antennas and the receive antenna. Discovering is a complementary process whereby W received symbols for W covered symbols are multiplied by the W chips of the same W -chip orthogonal sequence to obtain W discovered symbols, which are then accumulated to obtain an estimate of the transmitted symbol p . The discovering is performed at $L+1$ time delays to obtain the $L+1$ row vectors $\underline{h}(n)$, for $n = 0, 1, \dots, L$, for the channel impulse response of the MISO channel.

[0033] A time dispersive MISO channel may also be characterized by a two-dimensional frequency-domain channel frequency response matrix $\underline{\mathbf{H}}$ with dimensions of $N_F \times N_T$, where N_F is the number of frequency subbands and $N_F \geq (L+1)$. The matrix $\underline{\mathbf{H}}$ is composed of N_T channel frequency response vectors $\underline{\mathbf{h}}_j$, for $j = 1, 2, \dots, N_T$, i.e., $\underline{\mathbf{H}} = [\underline{\mathbf{h}}_1 \ \underline{\mathbf{h}}_2 \ \dots \ \underline{\mathbf{h}}_{N_T}]$. Each vector $\underline{\mathbf{h}}_j$ includes N_F frequency-domain values that may be obtained by performing an N_F -point discrete Fourier transform (DFT) on the $L+1$ time-domain values of the corresponding vector \underline{h}_j of the matrix $\underline{\mathcal{H}}$. For each transmit-receive antenna pair, there is thus a one-to-one correspondence between the time-domain channel impulse response vector \underline{h}_j and the frequency-domain channel frequency response vector $\underline{\mathbf{h}}_j$. The matrix $\underline{\mathbf{H}}$ is equivalently composed of N_F row vectors $\underline{\mathbf{h}}(k)$, for $k = 1, 2, \dots, N_F$, i.e., $\underline{\mathbf{H}} = [\underline{\mathbf{h}}^T(1) \ \underline{\mathbf{h}}^T(2) \ \dots \ \underline{\mathbf{h}}^T(N_F)]^T$, where $\underline{\mathbf{M}}^T$ is the transpose of $\underline{\mathbf{M}}$. Each row vector $\underline{\mathbf{h}}(k)$ includes N_T complex gain values for the frequency response between the N_T transmit antennas and the receive antenna for subband k . The DFT to obtain $\underline{\mathbf{h}}(k)$ may be expressed as:

$$\underline{\mathbf{h}}(k) = \sum_{n=0}^L \underline{h}(n) \cdot e^{-j(2\pi/N_F)(k-1)n}, \text{ for } k = 1, 2, \dots, N_F. \quad \text{Eq (2)}$$

[0034] The transmitter may perform eigensteering on a data symbol stream $s(n)$ prior to transmission via the MISO channel in order to achieve higher received signal-to-noise ratio (SNR) for the data symbol stream. The eigensteering may be performed using a frequency-independent steering vector $\underline{\mathbf{v}}_{\text{miso}}$, which may be derived to maximize the received SNR or based on some other criteria.

[0035] In one embodiment, the steering vector $\underline{\mathbf{v}}_{miso}$ for the transmitter is obtained by first computing an $N_T \times N_T$ correlation matrix $\underline{\mathbf{R}}_{miso}$ as follows:

$$\underline{\mathbf{R}}_{miso} = \sum_{n=0}^L \underline{\mathbf{h}}^H(n) \underline{\mathbf{h}}(n) = \frac{1}{N_F} \sum_{k=1}^{N_F} \underline{\mathbf{h}}^H(k) \underline{\mathbf{h}}(k) , \quad \text{Eq (3)}$$

where $\underline{\mathbf{h}}^H$ is the conjugate transpose of $\underline{\mathbf{h}}$. The matrix $\underline{\mathbf{R}}_{miso}$ may be viewed as an average of either $L+1$ individual correlation matrices of $\underline{\mathbf{h}}(n)$ for $L+1$ time delays or N_F individual correlation matrices of $\underline{\mathbf{h}}(k)$ for N_F subbands. The individual correlation matrices are given equal weight in equation (3). In another embodiment, the individual correlation matrices may be given unequal weights in the computation of $\underline{\mathbf{R}}_{miso}$. For example, each individual correlation matrix may be weighted by the energy associated with that matrix, which can be computed as described below.

[0036] Eigenvalue decomposition of the correlation matrix $\underline{\mathbf{R}}_{miso}$ is then performed as follows:

$$\underline{\mathbf{R}}_{miso} = \underline{\mathbf{V}}_{miso} \underline{\mathbf{\Lambda}}_{miso} \underline{\mathbf{V}}_{miso}^H , \quad \text{Eq (4)}$$

where $\underline{\mathbf{V}}_{miso}$ is an $N_T \times N_T$ unitary matrix whose columns are the eigenvectors of $\underline{\mathbf{R}}_{miso}$; and

$\underline{\mathbf{\Lambda}}_{miso}$ is an $N_T \times N_T$ diagonal matrix whose diagonal entries are the eigenvalues of $\underline{\mathbf{R}}_{miso}$.

A unitary matrix $\underline{\mathbf{M}}$ is characterized by the property $\underline{\mathbf{M}}^H \underline{\mathbf{M}} = \underline{\mathbf{I}}$, where $\underline{\mathbf{I}}$ is the identity matrix with ones along the diagonal and zeros elsewhere. The N_T eigenvectors of the unitary matrix $\underline{\mathbf{V}}_{miso}$, denoted as $\underline{\mathbf{v}}_j$ for $j=1, 2, \dots, N_T$, are thus orthogonal to one another. Moreover, the length of each eigenvector is equal to one, i.e.,

$$\|\underline{\mathbf{v}}_j\|^2 = \sum_{i=1}^{N_T} |v_{i,j}|^2 = 1, \text{ where } \underline{\mathbf{v}}_j = [v_{1,j} \ v_{2,j} \ \dots \ v_{N_T,j}]^T. \text{ The } N_T \text{ eigenvectors are also}$$

referred to as steering vectors and may be used for eigensteering by the transmitter and matched filtering by the receiver, as described below.

[0037] The matrix $\underline{\mathbf{R}}_{miso}$ is of dimension $N_T \times N_T$ and rank N_{miso} , where $N_{miso} \leq \min\{N_T, (L+1)\}$. The diagonal matrix $\underline{\mathbf{\Lambda}}_{miso}$ thus contains N_{miso} positive real values along the diagonal and zeros elsewhere. The largest non-zero entry is referred to

as the principal eigenvalue λ_{miso} of the matrix \mathbf{R}_{miso} and is indicative of the power gain for the spatial channel (or “time-domain eigenmode”) corresponding to that eigenvalue. The frequency-independent steering vector \mathbf{v}_{miso} to use for eigensteering is the “principal” eigenvector of \mathbf{R}_{miso} , which is the column of \mathbf{V}_{miso} that corresponds to the principal eigenvalue of \mathbf{R}_{miso} .

[0038] The transmitter performs eigensteering on the data symbol stream $s(n)$ with the steering vector \mathbf{v}_{miso} to obtain N_T transmit symbol streams $\mathbf{x}_{miso}(n)$, as follows:

$$\mathbf{x}_{miso}(n) = s(n) \cdot \mathbf{v}_{miso} \quad \text{Eq (5)}$$

With the eigensteering shown in equation (5), the data symbol stream $s(n)$ observes an effective channel that is a single-input single-output (SISO) channel with an effective channel impulse response of $\mathbf{h}(n)\mathbf{v}_{miso}$, for $n = 0, 1, \dots, L$. The N_T transmit symbol streams $\mathbf{x}_{miso}(n)$ are further processed and transmitted from the N_T transmit antennas to the receiver.

[0039] The receiver obtains a received symbol stream $y_{miso}(n)$ from the single receive antenna, which may be expressed as:

$$\begin{aligned} y_{miso}(n) &= \mathbf{h}(n) \otimes \mathbf{x}_{miso}(n) + n_{miso}(n) \\ &= \left(\sum_{j=0}^L \mathbf{h}(j) s(n-j) \mathbf{v}_{miso} \right) + n_{miso}(n) \end{aligned} \quad \text{Eq (6)}$$

where “ \otimes ” denotes a convolution and $n_{miso}(n)$ is additive white Gaussian noise (AWGN). The received symbol stream $y_{miso}(n)$ experiences intersymbol interference (ISI), which is a phenomenon whereby each symbol in a received stream acts as distortion to subsequent symbols in the received stream. Intersymbol interference may be mitigated through the use of OFDM in conjunction with a sufficiently long cyclic prefix, as described below. Alternatively, for a single-carrier MISO system, intersymbol interference may be mitigated through the use of appropriate temporal matched filtering in combination with equalization, as also described below.

[0040] The receiver can perform matched filtering of the received symbol stream $y_{miso}(n)$ in either the time domain or the frequency domain. The time-domain matched filtering may be expressed as:

$$\begin{aligned}\tilde{s}_{miso}(n) &= \underline{\mathbf{v}}_{miso}^H \underline{\mathbf{h}}^H(L-n) \otimes y_{miso}(n) , \\ &= \underline{\mathbf{v}}_{miso}^H \sum_{j=0}^L \underline{\mathbf{h}}^H(L-j) \cdot y_{miso}(n-j) ,\end{aligned}\tag{Eq (7)}$$

where $\tilde{s}_{miso}(n)$ denotes a detected symbol stream, which is an estimate of the data symbol stream $s(n)$ sent by the transmitter. The matched filter $\underline{\mathbf{m}}_{miso}(n) = \underline{\mathbf{v}}_{miso}^H \underline{\mathbf{h}}^H(L-n)$, for $n = 0, 1, \dots, L$, maximizes the received SNR.

[0041] An equalizer may be used to mitigate intersymbol interference due to time dispersion in the MIMO channel. The equalizer may be a minimum mean square error (MMSE) equalizer, a decision feedback equalizer (DFE), a maximum likelihood sequence estimator (MLSE), or some other type of equalizer. The equalizer may be implemented with an adaptive filter having coefficients that can be updated with pilot and/or data symbols and based on a particular criterion (e.g., minimum mean square error). The equalizer performs equalization on the detected symbol stream $\tilde{s}_{miso}(n)$ and provides a recovered symbol stream $\hat{s}_{miso}(n)$, which is a better estimate of the data symbol stream $s(n)$ sent by the transmitter. In general, the detected symbol stream $\tilde{s}_{miso}(n)$ may be provided directly as the recovered symbol stream $\hat{s}_{miso}(n)$ or may be post-processed (e.g., equalized) to obtain the recovered symbol stream $\hat{s}_{miso}(n)$.

[0042] The frequency-domain matched filtering may be expressed as:

$$\hat{s}_{miso}(k) = \underline{\mathbf{v}}_{miso}^H \underline{\mathbf{h}}^H(k) y_{miso}(k) , \text{ for } k = 1, 2, \dots, N_F , \tag{Eq (8)}$$

where $\hat{s}_{miso}(k)$ is the recovered symbol substream for subband k ; and

$y_{miso}(k)$ is the received symbol substream for subband k .

The N_F received symbol substreams $y_{miso}(k)$, for $k = 1, 2, \dots, N_F$, may be obtained by performing a fast Fourier transform (FFT) of each set of N_F symbols in the received symbol stream $y_{miso}(n)$. The matched filter $\underline{\mathbf{m}}_{miso}(k) = \underline{\mathbf{v}}_{miso}^H \underline{\mathbf{h}}^H(k)$, for $k = 1, 2, \dots, N_F$, is a complex-valued scalar that maximizes the received SNR for each subband. The N_F recovered symbol substreams for the N_F subbands may be multiplexed together to obtain the recovered symbol stream $\hat{s}_{miso}(n)$.

[0043] For both time-domain and frequency-domain matched filtering, the received SNR may be expressed as:

$$\text{SNR}_{\text{miso}} = \frac{P_{\text{total}}}{\sigma^2} \mathbf{v}_{\text{miso}}^H \mathbf{R}_{\text{miso}} \mathbf{v}_{\text{miso}} = \frac{P_{\text{total}}}{\sigma^2} \lambda_{\text{miso}} \quad , \quad \text{Eq (9)}$$

where P_{total} is the total transmit power used by the transmitter for the data symbol stream;
 σ^2 is the noise floor at the receiver; and
 λ_{miso} is the principal eigenvalue of \mathbf{R}_{miso} .

[0044] The capacity $C_{\text{miso}}^{\text{fi}}$ of the MISO channel with frequency-independent eigensteering may be determined using frequency-domain analysis and assuming that the same steering vector is used for all N_F subbands. The capacity $C_{\text{miso}}^{\text{fi}}$ may be expressed as:

$$C_{\text{miso}}^{\text{fi}} = \sum_{k=1}^{N_F} \log_2(1 + \text{SNR}(k)) = \sum_{k=1}^{N_F} \log_2(1 + \rho \cdot \mathbf{v}_{\text{miso}}^H \mathbf{R}(k) \mathbf{v}_{\text{miso}}) \quad , \quad \text{Eq (10)}$$

where ρ is the average received SNR as measured at the receive antenna, which is equal to the total receive power divided by the receiver noise σ^2 . The matrix $\mathbf{R}(k)$ is the correlation matrix of $\mathbf{h}(k)$, which may be obtained and decomposed as follows:

$$\mathbf{R}(k) = \mathbf{h}^H(k) \mathbf{h}(k) = \mathbf{U}(k) \mathbf{\Lambda}(k) \mathbf{U}^H(k) \quad , \quad \text{for } k=1, 2, \dots, N_F, \quad \text{Eq (11)}$$

where $\mathbf{\Lambda}(k)$ is the diagonal matrix of eigenvalues of $\mathbf{R}(k)$, and

$\mathbf{U}(k)$ is the unitary matrix of eigenvectors of $\mathbf{R}(k)$.

The quadratic term in equation (10) may be expressed as:

$$\mathbf{v}_{\text{miso}}^H \mathbf{R}(k) \mathbf{v}_{\text{miso}} = \mathbf{v}_{\text{miso}}^H \mathbf{U}(k) \mathbf{\Lambda}(k) \mathbf{U}^H(k) \mathbf{v}_{\text{miso}} = \mathbf{z}^H(k) \mathbf{\Lambda}(k) \mathbf{z}(k) \quad , \quad \text{Eq (12)}$$

where $\mathbf{z}(k) = \mathbf{U}^H(k) \mathbf{v}_{\text{miso}}$. Since $\mathbf{R}(k)$ has only one non-zero eigenvalue, equation (12) may be simplified as follows:

$$\mathbf{v}_{\text{miso}}^H \mathbf{R}(k) \mathbf{v}_{\text{miso}} = |z_1(k)|^2 \lambda(k) \quad , \quad \text{Eq (13)}$$

where $\lambda(k)$ is the non-zero eigenvalue of $\mathbf{R}(k)$, which is $\lambda(k) = \|\mathbf{h}(k)\|^2$ for a MISO channel, and $z_1(k)$ is the element of $\mathbf{z}(k)$ corresponding to the eigenvalue $\lambda(k)$. The capacity $C_{\text{miso}}^{\text{fi}}$ of the MISO channel with frequency-independent eigensteering may then be expressed as:

$$C_{\text{miso}}^{\text{fi}} = \sum_{k=1}^{N_F} \log_2(1 + \rho \cdot |z_1(k)|^2 \cdot \lambda(k)) \quad . \quad \text{Eq (14)}$$

- [0045] The capacity C_{miso}^n for the MISO channel without eigensteering at the transmitter (or equivalently with a steering vector $\underline{\mathbf{v}}=[g \ g \ \dots \ g]$, where $g=\sqrt{1/N_T}$) may be expressed as:

$$C_{miso}^n = \sum_{k=1}^{N_F} \log_2 \left(1 + \frac{\rho}{N_T} \cdot \lambda(k) \right) . \quad \text{Eq (15)}$$

In general, the capacity C_{miso}^{fi} of the MISO channel with frequency-independent eigensteering is greater than the capacity C_{miso}^n of the MISO channel without eigensteering.

- [0046] An exemplary method has been described above for obtaining the frequency-independent steering vector $\underline{\mathbf{v}}_{miso}$ for eigensteering at the transmitter in the MISO system. The steering vector may also be obtained in other manners, and this is within the scope of the invention.

- [0047] The frequency-independent eigensteering may also be used for a MISO system that employs OFDM (i.e., a MISO-OFDM system). The transmitter can perform eigensteering in the time-domain, as shown in equation (5), where $s(n)$ denotes a sequence of time-domain chips for OFDM symbols generated for the data stream by OFDM modulation. OFDM modulation is described below. The transmitter can also perform eigensteering in the frequency-domain on the data symbols for each subband, prior to the OFDM modulation to generate OFDM symbols. The receiver can perform matched filtering in the time-domain, as shown in equation (7), or the frequency-domain, as shown in equation (8).

2. MIMO System

- [0048] A time-dispersive MIMO channel with N_T transmit antennas and N_R receive antennas may be characterized by a three-dimensional time-domain channel impulse response matrix $\underline{\underline{\mathcal{H}}}$ with dimensions of $N_R \times N_T \times (L+1)$. The matrix $\underline{\underline{\mathcal{H}}}$ is composed of $L+1$ channel impulse response matrices $\underline{\mathcal{H}}(n)$, for $n=0, 1, \dots, L$, i.e., $\underline{\underline{\mathcal{H}}}=[\underline{\mathcal{H}}(0) \ \underline{\mathcal{H}}(1) \ \dots \ \underline{\mathcal{H}}(L)]$, which may be expressed as:

$$\underline{\mathcal{H}}(n) = \begin{bmatrix} \underline{h}_1(n) \\ \underline{h}_2(n) \\ \vdots \\ \underline{h}_{N_R}(n) \end{bmatrix} = \begin{bmatrix} h_{1,1}(n) & h_{1,2}(n) & \cdots & h_{1,N_T}(n) \\ h_{2,1}(n) & h_{2,2}(n) & \cdots & h_{2,N_T}(n) \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R,1}(n) & h_{N_R,2}(n) & \cdots & h_{N_R,N_T}(n) \end{bmatrix}, \quad \text{Eq (16)}$$

for $n = 0, 1, \dots, L$, where entry $h_{i,j}(n)$, for $i = 1, 2, \dots, N_R$, $j = 1, 2, \dots, N_T$, and $n = 0, 1, \dots, L$, is the coupling (i.e., complex gain) between transmit antenna j and receive antenna i for time delay n . The row vector $\underline{h}_i(n)$, for $i = 1, 2, \dots, N_R$ and $n = 0, 1, \dots, L$, includes N_T complex values for the channel gains between the N_T transmit antennas and receive antenna i for time delay n .

[0049] The channel impulse response may be estimated by the receiver based on pilot symbols sent by the transmitter. In one embodiment, the transmitter covers the pilot for each transmit antenna with an orthogonal code assigned to that antenna. The pilots sent from the N_T transmit antennas are covered by N_T orthogonal codes and may be individually recovered. At the receiver, the received pilot from each receive antenna i is discovered with the N_T orthogonal codes at a particular time delay to obtain the channel response between receive antenna i and each of the N_T transmit antennas for that time delay, i.e., one row of the matrix $\underline{\mathcal{H}}(n)$. The discovering is performed separately for all N_R receive antennas to obtain the N_R rows of the matrix $\underline{\mathcal{H}}(n)$. The discovering is also performed at $L+1$ time delays (i.e., for $n = 0, 1, \dots, L$) for each transmit-receive antenna pair to obtain the $L+1$ time-domain values for the channel impulse response for that transmit-receive antenna pair.

[0050] A time dispersive MIMO channel may also be characterized by a corresponding three-dimensional frequency-domain channel frequency response matrix $\underline{\underline{\mathbf{H}}}$ with dimensions of $N_R \times N_T \times N_F$, where $N_F > L$. The matrix $\underline{\underline{\mathbf{H}}}$ is composed of N_F channel frequency response matrices $\underline{\mathbf{H}}(k)$, for $k = 1, 2, \dots, N_F$, which can be obtained by computing an N_F -point discrete Fourier transform on the $L+1$ channel impulse response matrices $\underline{\mathcal{H}}(n)$, for $n = 0, 1, \dots, L$, as follows:

$$\underline{\mathbf{H}}(k) = \begin{bmatrix} \underline{\mathbf{h}}_1(k) \\ \underline{\mathbf{h}}_2(k) \\ \vdots \\ \underline{\mathbf{h}}_{N_R}(k) \end{bmatrix} = \sum_{n=0}^L \underline{\mathcal{H}}(n) \cdot e^{-j(2\pi/N_F)(k-1)n}, \quad \text{for } k = 1, 2, \dots, N_F. \quad \text{Eq (17)}$$

Each matrix $\underline{\mathbf{H}}(k)$, for $k=1, 2, \dots, N_F$, includes N_R row vectors $\underline{\mathbf{h}}_i(k)$, for $i=1, 2, \dots, N_R$, for the N_R receive antennas. Each row vector $\underline{\mathbf{h}}_i(k)$ includes N_T complex values for the channel gains between the N_T transmit antennas and receive antenna i for subband k . Each entry $\underline{h}_{i,j}$ of the matrix $\underline{\mathbf{H}}$, for $i=1, 2, \dots, N_R$ and $j=1, 2, \dots, N_T$, includes N_F frequency-domain values that may be obtained by taking the DFT of the $L+1$ time-domain values for a corresponding entry $\underline{h}_{i,j}$ of the matrix $\underline{\mathcal{H}}$. For each transmit-receive antenna pair, there is thus a one-to-one correspondence between the channel impulse response $\underline{h}_{i,j}$ and the channel frequency response $\underline{\mathbf{h}}_{i,j}$.

[0051] Frequency-independent eigensteering may be performed in various manners for a MIMO system. Some exemplary frequency-independent eigensteering schemes are described below.

A. Principal-Mode Eigensteering

[0052] For principal-mode eigensteering, a data symbol stream is transmitted on the principal spatial channel of the MIMO channel using a single frequency-independent steering vector $\underline{\mathbf{v}}_{pm}$. To obtain this steering vector, an $N_T \times N_T$ correlation matrix $\underline{\mathbf{R}}_{mimo}$ is first computed as follows:

$$\begin{aligned} \underline{\mathbf{R}}_{mimo} &= \sum_{n=0}^L \underline{\mathcal{H}}^H(n) \underline{\mathcal{H}}(n) = \frac{1}{N_F} \sum_{k=1}^{N_F} \underline{\mathbf{H}}^H(k) \underline{\mathbf{H}}(k) \quad , \\ &= \sum_{n=0}^L \sum_{j=1}^{N_T} \underline{h}_j^H(n) \underline{h}_j(n) = \frac{1}{N_F} \sum_{k=1}^{N_F} \sum_{j=1}^{N_T} \underline{\mathbf{h}}^H(k) \underline{\mathbf{h}}(k) \quad . \end{aligned} \quad \text{Eq (18)}$$

[0053] Eigenvalue decomposition of $\underline{\mathbf{R}}_{mimo}$ is then performed as follows:

$$\underline{\mathbf{R}}_{mimo} = \underline{\mathbf{V}}_{mimo} \underline{\Lambda}_{mimo} \underline{\mathbf{V}}_{mimo}^H \quad , \quad \text{Eq (19)}$$

where $\underline{\mathbf{V}}_{mimo}$ is a unitary matrix of eigenvectors of $\underline{\mathbf{R}}_{mimo}$ and $\underline{\Lambda}_{mimo}$ is a diagonal matrix whose diagonal entries are the eigenvalues of $\underline{\mathbf{R}}_{mimo}$.

[0054] A MIMO channel may be decomposed into N_S spatial channels, where $N_S \leq \min \{N_T, N_R\}$. The matrix $\underline{\mathbf{R}}_{mimo}$ is of rank N_S and the diagonal matrix $\underline{\Lambda}_{mimo}$ contains N_S non-negative real values along the diagonal. The largest non-zero diagonal entry is referred to as the principal eigenvalue λ_{mimo} of the matrix $\underline{\mathbf{R}}_{mimo}$. In an embodiment, the steering vector $\underline{\mathbf{v}}_{pm}$ to use for eigensteering is the principal

eigenvector of $\underline{\mathbf{R}}_{mimo}$, which is the column of $\underline{\mathbf{V}}_{mimo}$ that corresponds to the principal eigenvalue of $\underline{\mathbf{R}}_{mimo}$. The steering vector $\underline{\mathbf{v}}_{pm}$ may be viewed as being for the principal spatial channel of the “averaged” MIMO channel.

[0055] The transmitter performs eigensteering on the data symbol stream $s(n)$ with the steering vector $\underline{\mathbf{v}}_{pm}$ to obtain N_T transmit symbol streams $\underline{\mathbf{x}}_{pm}(n)$, as follows:

$$\underline{\mathbf{x}}_{pm}(n) = s(n) \cdot \underline{\mathbf{v}}_{pm} \quad . \quad \text{Eq (20)}$$

With the eigensteering shown in equation (20), the data symbol stream $s(n)$ observes an effective channel that is a single-input multiple-output (SIMO) channel with an effective channel impulse response of $\underline{\mathcal{H}}(n)\underline{\mathbf{v}}_{pm}$, for $n = 0, 1, \dots L$. The N_T transmit symbol streams $\underline{\mathbf{x}}_{pm}(n)$ are further processed and sent from the N_T transmit antennas to the receiver.

[0056] The receiver obtains N_R received symbol streams $\underline{\mathbf{y}}_{pm}(n)$ from the N_R receive antennas, which may be expressed as:

$$\underline{\mathbf{y}}_{pm}(n) = \underline{\mathcal{H}}(n) \otimes \underline{\mathbf{x}}_{pm}(n) + \underline{\mathbf{n}}_{mimo}(n) \quad , \quad \text{Eq (21)}$$

where $\underline{\mathbf{n}}_{mimo}(n)$ is additive white Gaussian noise with a mean vector of $\underline{\mathbf{0}}$ and a covariance matrix of $\underline{\Delta}_n = \sigma^2 \underline{\mathbf{I}}$, where $\underline{\mathbf{0}}$ is a vector of all zeros. The receiver can perform matched filtering of the received symbol streams $\underline{\mathbf{y}}_{pm}(n)$ in either the time domain or the frequency domain.

[0057] The time-domain matched filtering may be expressed as:

$$\tilde{s}_{pm}(n) = \underline{\mathbf{v}}_{pm}^H \underline{\mathcal{H}}^H(L-n) \otimes \underline{\mathbf{y}}_{pm}(n) \quad , \quad \text{for } n = 0, 1, \dots L. \quad \text{Eq (22)}$$

The receiver matched filter is $\underline{\mathbf{m}}_{pm}(n) = \underline{\mathbf{v}}_{pm}^H \underline{\mathcal{H}}^H(L-n)$, for $n = 0, 1, \dots L$, which includes N_R individual matched filters for the N_R receive antennas. The matched filter $m_{pm,i}(n)$ for each receive antenna has an impulse response of $m_{pm,i}(n) = \underline{\mathbf{v}}_{pm}^H \underline{\mathbf{f}}_i^H(L-n)$, for $n = 0, 1, \dots L$, that maximizes the received SNR for that receive antenna. The outputs of the N_R individual matched filters for the N_R receive antennas are summed to obtain the detected symbol stream $\tilde{s}_{pm}(n)$. Post processing (e.g., equalization) may be

performed on the detected symbol stream $\tilde{s}_{pm}(n)$ to obtain the recovered symbol stream $\hat{s}_{pm}(n)$.

[0058] The frequency-domain matched filtering may be expressed as:

$$\hat{s}_{pm}(k) = \underline{\mathbf{v}}_{pm}^H \underline{\mathbf{H}}^H(k) \underline{\mathbf{y}}_{pm}(k) \quad , \text{ for } k = 1, 2, \dots, N_F, \quad \text{Eq (23)}$$

where $\underline{\mathbf{y}}_{pm}(k)$ is the received symbol substreams for subband k , which can be obtained by performing an FFT of each set of N_F symbols in the received symbol streams $\underline{\mathbf{y}}_{pm}(n)$. The receiver matched filter is $\underline{\mathbf{m}}_{pm}(k) = \underline{\mathbf{v}}_{pm}^H \underline{\mathbf{H}}^H(k)$, for $k = 1, 2, \dots, N_F$, which includes N_R individual matched filters for the N_R receive antennas. The matched filter $\mathbf{m}_{pm,i}(k)$ for each receive antenna i has a response of $\mathbf{m}_{pm,i}(k) = \underline{\mathbf{v}}_{pm}^H \underline{\mathbf{h}}_i^H(k)$, for $k = 1, 2, \dots, N_F$. The outputs of the N_R individual matched filters for the N_R receive antennas for each subband k are summed to obtain the recovered symbol substream $\hat{s}_{pm}(k)$ for that subband. The N_F recovered symbol substreams for the N_F subbands may be multiplexed to obtain the recovered symbol stream $\hat{s}_{pm}(n)$.

[0059] For both the time-domain and frequency-domain matched filtering, the received SNR, averaged across the N_R receive antennas, may be expressed as:

$$\text{SNR}_{mimo}^{pm} = \frac{\rho}{N_R} \underline{\mathbf{v}}_{pm}^H \underline{\mathbf{R}}_{mimo} \underline{\mathbf{v}}_{pm} \quad . \quad \text{Eq (24)}$$

The matched filter $\underline{\mathbf{v}}_{pm}^H \underline{\mathcal{H}}^H(L-n)$, for $n = 0, 1, \dots, L$, maximizes the received SNR.

[0060] The capacity C_{mimo}^{pm} of the MIMO channel with principal-mode eigensteering may be expressed as:

$$C_{mimo}^{pm} = \sum_{k=1}^{N_F} \log_2(1 + \rho \cdot \underline{\mathbf{v}}_{pm}^H \underline{\mathbf{H}}^H(k) \underline{\mathbf{H}}(k) \underline{\mathbf{v}}_{pm}) \quad . \quad \text{Eq (25)}$$

The quadratic term in equation (25) may be expressed as:

$$\underline{\mathbf{v}}_{pm}^H \underline{\mathbf{H}}^H(k) \underline{\mathbf{H}}(k) \underline{\mathbf{v}}_{pm} = \sum_{\ell=1}^{N_T} \|\underline{\mathbf{v}}_{pm}^H \underline{\mathbf{u}}_{\ell}(k)\|^2 \cdot \lambda_{\ell}(k) \quad , \quad \text{Eq (26)}$$

where $\underline{\mathbf{u}}_{\ell}(k)$ is the eigenvector associated with the ℓ -th eigenvalue $\lambda_{\ell}(k)$ of the correlation matrix $\underline{\mathbf{R}}(k) = \underline{\mathbf{H}}^H(k) \underline{\mathbf{H}}(k)$. The capacity C_{mimo}^{pm} may then be expressed as:

$$C_{mimo}^{pm} = \sum_{k=1}^{N_F} \log_2 \left(1 + \rho \cdot \sum_{\ell=1}^{N_T} \|\underline{\mathbf{v}}_{pm}^H \underline{\mathbf{u}}_{\ell}(k)\|^2 \cdot \lambda_{\ell}(k) \right) \quad . \quad \text{Eq (27)}$$

B. Multi-mode Eigensteering

[0061] For multi-mode eigensteering, multiple data symbol streams are transmitted on multiple spatial channels of the MIMO channel using multiple frequency-independent steering vectors in a matrix $\underline{\mathbf{V}}_{mm}$, whose columns are the eigenvectors of the correlation matrix $\underline{\mathbf{R}}_{mimo}$. Since $\underline{\mathbf{R}}_{mimo}$ is of rank N_S , where $N_S \leq \min \{N_T, N_R\}$, the matrix $\underline{\mathbf{V}}_{mm}$ may include up to N_S eigenvectors $\underline{\mathbf{v}}_\ell$, for $\ell = 1, 2, \dots, N_S$, for up to N_S eigenmodes of $\underline{\mathbf{R}}_{mimo}$. For clarity, the following description assumes that all N_S eigenmodes are used for data transmission.

[0062] The transmitter performs eigensteering on N_S data symbol streams $\underline{\mathbf{s}}_{mm}(n)$ with the steering matrix $\underline{\mathbf{V}}_{mm}$ to obtain N_T transmit symbol streams $\underline{\mathbf{x}}_{mm}(n)$, as follows:

$$\underline{\mathbf{x}}_{mm}(n) = \underline{\mathbf{V}}_{mm} \underline{\mathbf{s}}(n) \quad , \quad \text{Eq (28)}$$

where $\underline{\mathbf{s}}_{mm}(n) = [s_1(n) \ s_2(n) \ \dots \ s_{N_S}(n)]^T$, $\underline{\mathbf{V}}_{mm} = [\underline{\mathbf{v}}_1 \ \underline{\mathbf{v}}_2 \ \dots \ \underline{\mathbf{v}}_{N_S}]$, and $N_S \leq \min \{N_T, N_R\}$ for a full-rank MIMO channel. Each data symbol stream $s_\ell(n)$, for $\ell = 1, 2, \dots, N_S$, is steered with a respective steering vector $\underline{\mathbf{v}}_\ell$ in the matrix $\underline{\mathbf{V}}_{mm}$. Each data symbol stream $s_\ell(n)$ observes an effective channel that is a SIMO channel with an effective channel impulse response of $\underline{\mathbf{H}}(n)\underline{\mathbf{v}}_\ell$, for $n = 0, 1, \dots, L$. The N_T transmit symbol streams $\underline{\mathbf{x}}_{mm}(n)$ are further processed and sent from the N_T transmit antennas to the receiver.

[0063] The receiver obtains N_R received symbol streams $\underline{\mathbf{y}}_{mm}(n)$ from the N_R receive antennas, which $\underline{\mathbf{y}}_{mm}(n) = \underline{\mathbf{H}}(n) \otimes \underline{\mathbf{x}}_{mm}(n) + \underline{\mathbf{n}}_{mimo}(n)$. For a time dispersive MIMO channel, the eigensteering with multiple frequency-independent steering vectors in the matrix $\underline{\mathbf{V}}_{mm}$ does not diagonalize the channel. Thus, when multiple spatial channels are used for data transmission using frequency-independent eigensteering, there will in general be cross-talk between the multiple symbol streams as well as intersymbol interference at the receiver.

[0064] The receiver can perform matched filtering of the received symbol streams $\underline{\mathbf{y}}_{mm}(n)$ in either the time domain or the frequency domain. The time-domain matched filtering may be expressed as:

$$\tilde{\underline{s}}_{mm}(n) = \underline{\mathbf{V}}_{mm}^H \underline{\mathcal{H}}^H(L-n) \otimes \underline{y}_{mm}(n) , \quad \text{Eq (29)}$$

where $\tilde{\underline{s}}_{mm}(n)$ denotes N_S detected symbol streams. The receiver matched filter is $\underline{\mathcal{M}}_{mm}(n) = \underline{\mathbf{V}}_{mm}^H \underline{\mathcal{H}}^H(L-n)$, for $n = 0, 1, \dots, L$, which includes N_R individual matched filters for the N_R receive antennas. The matched filter $\underline{m}_{mm,i}(n)$ for each receive antenna has an impulse response of $\underline{m}_{mm,i}(n) = \underline{\mathbf{V}}_{mm}^H \underline{h}_i^H(L-n)$, for $n = 0, 1, \dots, L$. The output of the matched filter for each receive antenna includes N_S filtered symbol substreams corresponding to the N_S steering vectors (i.e., N_S columns of $\underline{\mathbf{V}}_{mm}$). The N_R filtered symbol substreams from the N_R matched filters for each steering vector are combined to obtain the detected symbol stream $\tilde{s}_\ell(n)$ for that steering vector. N_S detected symbol streams $\tilde{\underline{s}}_{mm}(n)$ are obtained for the N_S data symbols $\underline{s}_{mm}(n)$ sent by the transmitter.

[0065] The frequency-domain matched filtering may be expressed as:

$$\tilde{\underline{s}}_{mm}(k) = \underline{\mathbf{V}}_{mm}^H \underline{\mathbf{H}}^H(k) \underline{y}_{mm}(k) , \quad \text{for } k = 1, 2, \dots, N_F , \quad \text{Eq (30)}$$

where $\underline{y}_{mm}(k)$ is the received symbol substream for subband k , which is obtained by performing an FFT of each set of N_F symbols in the received symbol stream $\underline{y}_{mm}(n)$. The receiver matched filter is $\underline{\mathbf{M}}_{mm}(k) = \underline{\mathbf{V}}_{mm}^H \underline{\mathbf{H}}^H(k)$, for $k = 1, 2, \dots, N_F$, which includes N_R individual matched filters for the N_R receive antennas. The matched filter $\underline{m}_{mm,i}(k)$ for each receive antenna has a response of $\underline{m}_{mm,i}(k) = \underline{\mathbf{V}}_{mm}^H \underline{\mathbf{h}}_i^H(k)$, for $k = 1, 2, \dots, N_F$. For each subband k , the output of the matched filter for each receive antenna includes N_S filtered symbol substreams corresponding to the N_S transmit steering vectors. For each subband k , the N_R filtered symbol substreams from the N_R matched filters for each steering vector are combined to obtain the detected symbol substream $\tilde{s}_\ell(k)$ for that steering vector. The N_F detected symbol substreams for the N_F subbands for each steering vector are then multiplexed to obtain the detected symbol stream $\tilde{s}_\ell(n)$ for the data symbol stream $s_\ell(n)$ sent with that steering vector. N_S detected symbol streams $\tilde{\underline{s}}_{mm}(n)$ are obtained for N_S data symbol streams $\underline{s}_{mm}(n)$ sent by the transmitter.

[0066] As noted above, if multiple data symbol streams are transmitted simultaneously, then there is cross-talk between these data symbol streams at the receiver for a time

dispersive MIMO channel. A space-time or “joint” equalizer may be used to mitigate the cross-talk and intersymbol interference due to time dispersion in the MIMO channel. The space-time equalizer may be a minimum mean square error linear equalizer (MMSE-LE), a decision feedback equalizer (DFE), a maximum likelihood sequence estimator (MLSE), or some other type of equalizer. The space-time equalizer may be designed to operate on the N_S detected symbol streams $\tilde{\underline{s}}_{mm}(n)$ in both time and space domains to obtain N_S recovered symbol streams $\hat{\underline{s}}_{mm}(n)$, which are improved estimates of the data symbol streams $\underline{s}_{mm}(n)$ sent by the transmitter. Exemplary designs of the MMSE-LE, DFE, and MLSE are described in commonly assigned U.S. Patent Application Serial No. 09/993,087, entitled “Multiple-Access Multiple-Input Multiple-Output (MIMO) Communication System,” filed November 6, 2001.

[0067] The space-time equalizer may also implement a successive equalization and interference cancellation receiver processing technique, which successively recovers one data symbol stream at a time. As each data symbol stream is recovered, the interference it causes to the remaining, not yet recovered data symbol streams is estimated and canceled from the detected symbol streams to obtain “modified” symbol streams. The modified symbol streams are then processed to recover the next data symbol stream. The process is repeated until all N_S data symbol streams are recovered. By removing the interference due to each recovered data symbol stream, the not yet recovered data symbol streams experience less interference and may achieve higher SNRs. The successive equalization and interference cancellation receiver processing technique is also described in the aforementioned U.S. Patent Application Serial No. 09/993,087.

[0068] The capacity C_{mimo}^{mm} of the MIMO channel with multi-mode eigensteering may be expressed as:

$$C_{mimo}^{mm} = \sum_{k=1}^{N_F} \log_2 \left| \mathbf{I} + \frac{\rho}{N_S} \cdot \underline{\mathbf{V}}_{mm}^H \underline{\mathbf{R}}(k) \underline{\mathbf{V}}_{mm} \right|, \quad \text{Eq (31)}$$

where $|\underline{\mathbf{M}}|$ denotes the determinant of $\underline{\mathbf{M}}$. A correlation matrix $\tilde{\underline{\mathbf{R}}}(k)$ may be defined as $\tilde{\underline{\mathbf{R}}}(k) = \underline{\mathbf{V}}_{mm}^H \underline{\mathbf{R}}(k) \underline{\mathbf{V}}_{mm}$. The eigenvalues of $\tilde{\underline{\mathbf{R}}}(k)$ may be computed and denoted as $\tilde{\lambda}_\ell(k)$, for $\ell = 1, 2, \dots, N_S$ and $k = 1, 2, \dots, N_F$. The capacity C_{mimo}^{mm} of the MIMO channel with multi-mode eigensteering may then be expressed as:

$$C_{mimo}^{mm} = \sum_{k=1}^{N_F} \sum_{\ell=1}^{N_S} \log_2 \left(1 + \frac{\rho}{N_S} \cdot \tilde{\lambda}_\ell(k) \right) . \quad \text{Eq (32)}$$

C. Main Path Eigensteering

[0069] For main path eigensteering, a data symbol stream is transmitted on the principal spatial channel for the main propagation path of the MIMO channel using a single frequency-independent steering vector $\underline{\mathbf{v}}_{mp}$. As noted above, a time dispersive MIMO channel can be characterized by $L+1$ channel impulse response matrices $\underline{\mathcal{H}}(n)$, for $n=0, 1, \dots, L$. In an embodiment, the main path is defined as the propagation path with the most received energy. The energy $E(n)$ of each channel impulse response matrix $\underline{\mathcal{H}}(n)$, for $n=0, 1, \dots, L$, may be computed as follows:

$$E(n) = \|\underline{\mathcal{H}}(n)\|^2 = \sum_{j=1}^{N_R} \sum_{i=1}^{N_T} |\hat{h}_{i,j}(n)|^2, \text{ for } n=0, 1, \dots, L. \quad \text{Eq (33)}$$

The energy $E(n)$ is also (1) the trace of the correlation matrix $\underline{\mathcal{R}}(n) = \underline{\mathcal{H}}^H(n)\underline{\mathcal{H}}(n)$ and (2) the square of the Frobenius norm of the channel impulse response matrix $\underline{\mathcal{H}}(n)$. The largest energy, E_{\max} , for all $L+1$ time delays is then determined as:

$$E_{\max} = \max_{n=0 \dots L} \{E(n)\} . \quad \text{Eq (34)}$$

The main path delay n_{mp} is equal to the time delay of the channel impulse response matrix with the highest energy E_{\max} . The channel response matrix $\underline{\mathbf{H}}_{mp}$ for the main path is then $\underline{\mathbf{H}}_{mp} = \underline{\mathcal{H}}(n_{mp})$.

[0070] A correlation matrix $\underline{\mathbf{R}}_{mp}$ of $\underline{\mathbf{H}}_{mp}$ is computed as $\underline{\mathbf{R}}_{mp} = \underline{\mathbf{H}}_{mp}^H \underline{\mathbf{H}}_{mp}$. Eigenvalue decomposition of the correlation matrix $\underline{\mathbf{R}}_{mp}$ may be expressed as:

$$\underline{\mathbf{R}}_{mp} = \underline{\mathbf{V}}_{mp} \underline{\Lambda}_{mp} \underline{\mathbf{V}}_{mp}^H, \quad \text{Eq (35)}$$

where $\underline{\mathbf{V}}_{mp}$ is a unitary matrix of eigenvectors of $\underline{\mathbf{R}}_{mp}$ and $\underline{\Lambda}_{mp}$ is a diagonal matrix of eigenvalues of $\underline{\mathbf{R}}_{mp}$.

[0071] The matrix $\underline{\mathbf{R}}_{mp}$ is of rank N_S and the diagonal matrix $\underline{\Lambda}_{mp}$ contains N_S non-negative real values along the diagonal. The frequency-independent steering vector $\underline{\mathbf{v}}_{mp}$

to use for eigensteering is the principal eigenvector of \mathbf{R}_{mp} , which is the column of \mathbf{V}_{mp} that corresponds to the largest eigenvalue of \mathbf{R}_{mp} .

- [0072] The transmitter performs eigensteering on the data symbol stream $s(n)$ with the steering vector \mathbf{v}_{mp} to obtain N_T transmit symbol streams $\mathbf{x}_{mp}(n)$, as follows:

$$\mathbf{x}_{mp}(n) = s(n) \cdot \mathbf{v}_{mp} \quad \text{Eq (36)}$$

The spatial processing shown in equation (36) steers the transmit power in the direction of the principal spatial channel for the strongest propagation path.

- [0073] The receiver can perform matched filtering of the received symbol streams $\mathbf{y}_{mp}(n)$, which is $\mathbf{y}_{mp}(n) = \mathbf{H}(n) \otimes \mathbf{x}_{mp}(n) + \mathbf{n}_{mimo}(n)$, in either the time domain or the frequency domain. The time-domain matched filtering may be expressed as:

$$\tilde{s}_{mp}(n) = \mathbf{v}_{mp}^H \mathbf{H}^H(L-n) \otimes \mathbf{y}_{mp}(n) \quad , \text{ for } n = 0, 1, \dots, L \quad \text{Eq (37)}$$

The detected symbol stream $\tilde{s}_{mp}(n)$ may be post processed (e.g., equalized) to obtain the recovered symbol stream $\hat{s}_{mp}(n)$.

- [0074] The frequency-domain matched filtering may be expressed as:

$$\hat{s}_{mp}(k) = \mathbf{v}_{mp}^H \mathbf{H}^H(k) \mathbf{y}_{mp}(k) \quad , \text{ for } k = 1, 2, \dots, N_F \quad \text{Eq (38)}$$

The N_F recovered symbol substreams $\hat{s}_{mp}(k)$, for $k = 1, 2, \dots, N_F$, for the N_F subbands may be multiplexed to obtain the recovered symbol stream $\hat{s}_{mp}(n)$.

- [0075] In general, the receiver processing for main path eigensteering may be performed similar to that described above for principal-mode eigensteering. However, the matched filtering is performed based on the steering vector \mathbf{v}_{mp} for the principal spatial channel of the main path instead of the steering vector \mathbf{v}_{pm} for the principal spatial channel of the “averaged” MIMO channel.

D. Receiver Eigensteering

- [0076] For receiver eigensteering, the MIMO channel is viewed as being composed of N_R MISO channels for N_R receive antennas. N_R frequency-independent steering vectors may be obtained for the N_R MISO channels in similar manner as that described above for the MISO system.

[0077] As shown in equation (16), the matrix $\underline{\mathcal{H}}(n)$ for the MIMO channel is composed of N_R channel impulse response vectors $\underline{h}_i(n)$, for $i = 1, 2, \dots, N_R$. Each row vector $\underline{h}_i(n)$ includes the channel impulse response between the N_T transmit antennas and receive antenna i . An $N_T \times N_T$ correlation matrix $\underline{\mathbf{R}}_i$ may be computed for each receive antenna, as follows:

$$\underline{\mathbf{R}}_i = \sum_{n=0}^L \underline{h}_i^H(n) \underline{h}_i(n) = \frac{1}{N_F} \sum_{k=1}^{N_F} \underline{h}_i^H(k) \underline{h}_i(k), \text{ for } i = 1, 2, \dots, N_R. \quad \text{Eq (39)}$$

Eigenvalue decomposition of the correlation matrix $\underline{\mathbf{R}}_i$ for each receive antenna may be performed as follows:

$$\underline{\mathbf{R}}_i = \underline{\mathbf{V}}_i \underline{\Lambda}_i \underline{\mathbf{V}}_i^H, \text{ for } i = 1, 2, \dots, N_R, \quad \text{Eq (40)}$$

where $\underline{\mathbf{V}}_i$ is a unitary matrix whose columns are the eigenvectors of $\underline{\mathbf{R}}_i$; and

$\underline{\Lambda}_i$ is a diagonal matrix whose diagonal entries are the eigenvalues of $\underline{\mathbf{R}}_i$.

[0078] Since each $\underline{h}_i(n)$ is a row vector for one receive antenna, the correlation matrix $\underline{\mathbf{R}}_i$ has rank of less than or equal to $\min \{(L+1), N_T\}$. For each receive antenna i , the frequency-independent steering vector $\underline{\mathbf{v}}_{rx,i}$ that maximizes the received SNR for that receive antenna is the column of $\underline{\mathbf{V}}_i$ that corresponds to the maximum non-zero eigenvalue of $\underline{\mathbf{R}}_i$. N_R steering vectors $\underline{\mathbf{v}}_{rx,i}$, for $i = 1, 2, \dots, N_R$, are obtained for the N_R receive antennas and may be represented by an $N_T \times N_R$ matrix $\underline{\mathbf{V}}_{rx} = [\underline{\mathbf{v}}_{rx,1} \ \underline{\mathbf{v}}_{rx,2} \ \dots \ \underline{\mathbf{v}}_{rx,N_R}]$.

[0079] One or multiple data symbol streams may be transmitted with receiver eigensteering. If one data symbol stream $s(n)$ is transmitted, then the transmitter performs eigensteering on this data symbol stream with each of the N_R steering vectors to obtain N_T transmit symbol streams $\underline{\chi}_{rx}(n)$, as follows:

$$\underline{\chi}_{rx}(n) = s(n) \cdot \sum_{i=1}^{N_R} \underline{\mathbf{v}}_{rx,i}. \quad \text{Eq (41)}$$

[0080] Again, if one data symbol stream is transmitted, then the receiver can perform matched filtering of the N_R received symbol streams $\underline{\mathbf{y}}_{rx}(n)$, which is $\underline{\mathbf{y}}_{rx}(n) = \underline{\mathcal{H}}(n) \otimes \underline{\chi}_{rx}(n) + \underline{\mathbf{n}}_{mimo}(n)$, in either the time domain or the frequency domain.

For the time-domain technique, the matched filtering is first performed for each receive antenna, as follows:

$$\tilde{s}_{rx,i}(n) = \mathbf{v}_{rx,i}^H \mathbf{f}_i^H(L-n) \otimes \mathbf{y}_{mp}(n) \quad , \text{ for } i = 1, 2, \dots, N_R \quad , \quad \text{Eq (42)}$$

where $\tilde{s}_{rx,i}(n)$ is the filtered symbol stream for receive antenna i . The N_R filtered symbol streams for all N_R receive antennas are then combined to obtain the detected symbol stream $\tilde{s}_{rx}(n)$, as follows:

$$\tilde{s}_{rx}(n) = \sum_{i=1}^{N_R} \tilde{s}_{rx,i}(n) \quad . \quad \text{Eq (43)}$$

The detected symbol stream $\tilde{s}_{rx}(n)$ may be post-processed (e.g., equalized) to obtain the recovered symbol stream $\hat{s}_{rx}(n)$, which is an estimate of the transmitted data symbol stream $s(n)$.

[0081] For the frequency-domain technique, the matched filtering is first performed for each subband of each receive antenna, as follows:

$$\hat{s}_{rx,i}(k) = \mathbf{v}_{rx,i}^H \mathbf{h}_i^H(k) \mathbf{y}_{rx}(k) \quad , \text{ for } i = 1, 2, \dots, N_R \text{ and } k = 1, 2, \dots, N_F \quad , \quad \text{Eq (44)}$$

where $\hat{s}_{rx,i}(k)$ is the filtered symbol substream for subband k of receive antenna i . The N_R filtered symbol substreams for all N_R receive antennas for subband k are then combined to obtain the detected symbol substream $\hat{s}_{rx}(k)$ for subband k , as follows:

$$\hat{s}_{rx}(k) = \sum_{i=1}^{N_R} \hat{s}_{rx,i}(k) \quad , \text{ for } k = 1, 2, \dots, N_F \quad . \quad \text{Eq (45)}$$

The N_F detected symbol substreams $\hat{s}_{rx}(k)$ for all N_F subbands may be multiplexed together to obtain the recovered symbol stream $\hat{s}_{rx}(n)$.

[0082] If multiple (N_D) data symbol streams are transmitted, where $N_S \geq N_D > 1$, then each data symbol stream may be steered to a respective set of one or more receive antennas. The transmitter performs eigensteering for each data symbol stream $s_\ell(n)$ with a set of N_ℓ steering vectors for a set of N_ℓ receive antennas to which that data symbol stream is steered, where $N_\ell \geq 1$. The eigensteering at the transmitter for each data symbol stream $s_\ell(n)$ may be expressed as:

$$\mathbf{x}_{rx,\ell}(n) = s_\ell(n) \cdot \sum_{j=1}^{N_\ell} \mathbf{v}_{rx,\ell,j} \quad , \text{ for } \ell = 1, 2, \dots, N_D \quad , \quad \text{Eq (46)}$$

where $\underline{\chi}_{rx,\ell}(n)$ is the N_T transmit symbol substreams for data symbol stream $s_\ell(n)$, and $\underline{v}_{rx,\ell,j}$, for $j = 1 \dots N_\ell$, are the N_ℓ steering vectors for data symbol stream $s_\ell(n)$. The N_D sets of N_T transmit symbol substreams for all N_D data symbol streams are then combined to obtain the N_T transmit symbol streams $\underline{\chi}_{rx}(n)$, as follows:

$$\underline{\chi}_{rx}(n) = \sum_{\ell=1}^{N_D} \underline{\chi}_{rx,\ell}(n) \quad . \quad \text{Eq (47)}$$

[0083] The receiver can perform matched filtering of the received symbol stream $y_i(n)$ for each receive antenna in either the time domain as shown in equation (42) or the frequency domain as shown in equation (44). The receiver can then combine the filtered symbol substreams $\tilde{s}_{\ell,j}(n)$, for $j = 1 \dots N_\ell$, from all receive antennas used for each data symbol stream $s_\ell(n)$ to obtain the detected symbol stream $\tilde{s}_\ell(n)$ for that data symbol stream. A space-time equalizer may be used to equalize the N_D detected symbol streams $\tilde{\underline{s}}_{rx}(n)$ to obtain N_D recovered symbol streams $\hat{\underline{s}}_{rx}(n)$.

[0084] The frequency-independent eigensteering may also be used for a MIMO-OFDM system. The transmitter can perform eigensteering in the time-domain, as shown in equations (20), (28), (36) and (41), where $s(n)$ and $\underline{s}(n)$ denote sequence(s) of time-domain chips for OFDM symbols generated for the data stream(s) by OFDM modulation. The transmitter can also perform eigensteering in the frequency-domain on the data symbols for each subband, prior to the OFDM modulation to generate OFDM symbols. The receiver can perform matched filtering in the time-domain, as shown in equations (22), (29), (37), (42) and (43). The receiver can also perform matched filtering in the frequency-domain, as shown in equations (23), (30), (38), (44) and (45).

3. MISO System

[0085] FIG. 1 shows a block diagram of a transmitter 110 and a receiver 150 in a MISO system 100. At transmitter 110, a transmit (TX) data processor 120 receives a data stream $d(n)$ from a data source 112, processes (e.g., encodes, interleaves, and modulates) the data stream in accordance with a selected transmission mode, and provides a data symbol stream $s(n)$. The selected transmission mode may be associated with a particular data rate, a particular coding scheme or code rate, and a particular

modulation scheme to use for the data stream, which are respectively indicated by the data rate, coding, and modulation controls provided by a controller 140.

[0086] A TX spatial processor 130 receives the data symbol stream $s(n)$ and may perform wideband processing such as spectral spreading or multi-carrier modulation, as described below. TX spatial processor 130 further performs eigensteering based on the frequency-independent steering vector \underline{v}_{miso} (which is also referred to as a TX steering vector) provided by controller 140. TX spatial processor 130 also multiplexes pilot in with the data and provides N_T transmit chip streams $\underline{c}_{miso}(n)$ for the N_T transmit antennas. The processing by TX data processor 120 and TX spatial processor 130 is described in further detail below.

[0087] A transmitter unit (TMTR) 132 receives and conditions (e.g., converts to analog, frequency upconverts, filters, and amplifies) the N_T transmit chip streams to obtain N_T modulated signals. Each modulated signal is then transmitted from a respective transmit antenna (not shown in FIG. 1) and via the MISO channel to receiver 150. The MISO channel distorts the transmitted signals with a channel impulse response $\underline{h}(n)$ and further degrades the transmitted signals with additive white Gaussian noise and possibly interference from other transmission sources.

[0088] At receiver 150, the N_T transmitted signals are received by a single receive antenna (not shown in FIG. 1), and the received signal is provided to a receiver unit (RCVR) 154. Receiver unit 154 conditions and digitizes the received signal to obtain a stream of samples for the transmitted data and pilot. Receiver unit 154 provides a received symbol stream $y_{miso}(n)$ (for the data) to a receive (RX) spatial processor 160 and received pilot symbols (for the pilot) to a channel estimator 172. RX spatial processor 160 performs matched filtering of the received symbol stream $y_{miso}(n)$ with a matched filter and provides a recovered symbol stream $\hat{s}_{miso}(n)$, which is an estimate of the data symbol stream $s(n)$ sent by transmitter 110. An RX data processor 170 then processes (e.g., demodulates, deinterleaves, and decodes) the recovered symbol stream in accordance with the selected transmission mode to obtain a decoded data stream $\hat{d}(n)$, which is an estimate of the data stream $d(n)$ sent by transmitter 110. RX data processor 170 may further provide the status of each received data packet.

- [0089] Channel estimator 172 processes the received pilot symbols to obtain channel gain and SNR estimates for the MISO channel. A matrix computation unit 174 then processes the channel gain estimates to obtain the frequency-independent steering vector $\underline{\mathbf{v}}_{miso}$ for TX spatial processor 130 and the matched filter for RX spatial processor 160. A transmission mode selector 176 receives the SNR estimates from channel estimator 172 and the packet status from RX data processor 170, determines a suitable transmission mode for the data stream, and provides the selected transmission mode to a controller 180.
- [0090] Controller 180 receives the steering vector $\underline{\mathbf{v}}_{miso}$ from computation unit 174 and the selected transmission mode from transmission mode selector 176 and assembles feedback information for transmitter 110. The feedback information is sent to transmitter 110 and used to adjust the processing of the data stream $\mathcal{d}(n)$ sent to receiver 150. For example, transmitter 110 may use the feedback information to adjust the data rate, the coding scheme, the modulation scheme, the eigensteering, or any combination thereof, for the data stream sent to receiver 150.
- [0091] Controllers 140 and 180 direct the operation at transmitter 110 and receiver 150, respectively. Memory units 142 and 182 provide storage for program codes and data used by controllers 140 and 180, respectively. Memory units 142 and 182 may be internal to controllers 140 and 180, as shown in FIG. 1, or external to these controllers.
- [0092] FIG. 2 shows a block diagram of an embodiment of TX data processor 120 in FIG. 1. Within TX data processor 120, an encoder 212 receives and codes the data stream $\mathcal{d}(n)$ based on a coding scheme indicated by the coding control and provides code bits. The data stream may carry one or more data packets, and each data packet is typically coded separately to obtain a coded data packet. The coding increases the reliability of the data transmission. The coding scheme may include cyclic redundancy check (CRC) coding, convolutional coding, turbo coding, block coding, and so on, or a combination thereof. A channel interleaver 214 interleaves the code bits based on an interleaving scheme, which may be indicated by an interleaving control if the interleaving is dependent on transmission mode. The interleaving provides time, frequency, and/or spatial diversity for the code bits.
- [0093] A symbol mapping unit 216 maps the interleaved bits based on a modulation scheme indicated by the modulation control and provides a stream of modulation

symbols (or simply, “data symbols”). Unit 216 groups each set of B interleaved bits to form a B -bit binary value, where $B \geq 1$, and further maps each B -bit value to a specific modulation symbol based on the modulation scheme (e.g., QPSK, M-PSK, or M-QAM, where $M = 2^B$). Each modulation symbol is a complex value in a signal constellation defined by the modulation scheme.

[0094] **FIG. 3A** shows a block diagram of a TX spatial processor 130a, which is an embodiment of TX spatial processor 130 in FIG. 1. TX spatial processor 130a includes an eigensteering unit 330, a TX pilot processor 340, and a multiplexer (MUX) 350.

[0095] Eigensteering unit 330 includes N_T multipliers 332a through 332t, one multiplier 332 for each of the N_T transmit antennas. Each multiplier 332 receives the data symbol stream $s(n)$ and a respective element $v_{miso,j}$ of the TX steering vector \underline{v}_{miso} , multiplies each data symbol with the element $v_{miso,j}$, and provides a transmit symbol stream. Multipliers 332a through 332t perform frequency-independent eigensteering as shown in equation (5).

[0096] TX pilot processor 340 includes N_T multipliers 342a through 342t, one multiplier 342 for each of the N_T transmit antennas. Each multiplier 342 receives the pilot symbol and a unique orthogonal sequence w_j assigned to its transmit antenna, multiplies the pilot symbol with the orthogonal sequence w_j , and provides a sequence of covered pilot symbols. Multipliers 342a through 342t generate N_T orthogonal pilots for the N_T transmit antennas, which may be used for channel estimation by receiver 150.

[0097] Multiplexer 350 includes N_T multiplexers 352a through 352t, one multiplexer 352 for each of the N_T transmit antennas. Each multiplexer 352 receives and multiplexes the transmit symbols from an associated multiplier 332 with the covered pilot symbols from an associated multiplier 342 and provides a respective stream of transmit chips $c_j(n)$. The pilot may be multiplexed with the data using time division multiplexing (TDM), as shown in FIG. 3A, code division multiplexing (CDM), subband multiplexing, or some other multiplexing scheme. In any case, multiplexers 352a through 352t provide N_T transmit chip streams $c_j(n)$, for $j=1, 2, \dots, N_T$, for the N_T transmit antennas.

[0098] Transmitter unit 132 includes N_T transmitters 362a through 362t, one transmitter 362 for each of the N_T transmit antennas. Each transmitter 362 receives and conditions

a respective transmit chip stream to generate a modulated signal, which is then transmitted from an associated antenna 134.

[0099] **FIG. 3B** shows a block diagram of a TX spatial processor 130b, which is another embodiment of TX spatial processor 130 in FIG. 1. TX spatial processor 130b performs spectral spreading in the time domain and includes a spreader 310, eigensteering unit 330, TX pilot processor 340, and multiplexer 350.

[0100] Within TX spatial processor 130b, spreader 310 receives and spectrally spreads the data symbol stream $s(n)$ with a pseudo-random number (PN) sequence and provides a stream of spread data symbols. The spreading is especially applicable for a low rate data symbol stream to spectrally spread the data over the entire system bandwidth. The spreading may be performed in similar manner as for a CDMA system, which is well known in the art. The eigensteering is then performed on the spread data symbol stream (instead of the data symbol stream), as described above for FIG. 3A, to obtain N_T transmit chip streams for the N_T transmit antennas.

[0101] **FIG. 3C** shows a block diagram of a TX spatial processor 130c, which is yet another embodiment of TX spatial processor 130 in FIG. 1. TX spatial processor 130c performs OFDM modulation and includes an OFDM modulator 320, eigensteering unit 330, TX pilot processor 340, and multiplexer 350.

[0102] Within TX spatial processor 130c, an OFDM modulator 320 receives and performs OFDM modulation on the data symbol stream $s(n)$. OFDM effectively partitions the overall system bandwidth into multiple (N_F) orthogonal subbands, which are also commonly referred to as tones, bins, and frequency subchannels. With OFDM, each subband is associated with a respective carrier that may be modulated with data. For each OFDM symbol period, one data or pilot symbol may be transmitted on each subband used for transmission, and a signal value of zero is provided for each unused subband. Within OFDM modulator 320, an inverse fast Fourier transform (IFFT) unit receives a set of data/pilot symbols and zeros for the N_F subbands for each OFDM symbol period, transforms the set of data/pilot symbols and zeros to the time domain using an inverse fast Fourier transform, and provides a transformed symbol that contains N_F time-domain chips. A cyclic prefix generator then repeats a portion of each transformed symbol to obtain an OFDM symbol that contains $N_F + N_{cp}$ chips, where N_{cp} is the number of chips repeated. The cyclic prefix is used to combat frequency

selective fading caused by time dispersion in the channel. OFDM modulator 320 provides a stream of data chips for a stream of OFDM symbols.

[0103] Eigensteering is then performed on the data chip stream (instead of the data symbol stream), as described above for FIG. 3A, to obtain N_T transmit chip streams for the N_T transmit antennas. Alternatively, the data symbol stream may be demultiplexed into N_S data symbol substreams and eigensteering may be performed on each data symbol substream. In this case, the same steering vector \underline{v}_{miso} is used for all subbands. OFDM modulation may then be performed on the output of the eigensteering for all subbands of each transmit antenna to obtain the transmit chip stream for that transmit antenna. In general, the eigensteering may be performed in either the time domain or the frequency domain. However, eigensteering in the time domain may require fewer multiplications and may thus be simpler to implement.

[0104] FIG. 4A shows a block diagram of an RX spatial processor 160a, which is one embodiment of RX spatial processor 160 in FIG. 1 and may be used in conjunction with TX spatial processor 130a in FIG. 3A. An antenna 152 receives the N_T transmitted signals from transmitter 110 and provides the received signal. Receiver unit 154 conditions, digitizes, and pre-processes the received signal and provides the received symbol stream $y_{miso}(n)$. The pre-processing may include filtering, resampling, sample rate conversion, and so on.

[0105] Within RX spatial processor 160a, a matched filter 410 performs matched filtering of the received symbol stream $y_{miso}(n)$ with the matched filter $m_{miso}(n) = \underline{v}_{miso}^H \underline{f}^H(L-n)$, as shown in equation (7), and provides the detected symbol stream $\tilde{s}_{miso}(n)$. An equalizer 412 then performs equalization on the detected symbol stream and provides the recovered symbol stream $\hat{s}_{miso}(n)$. Equalizer 412 may implement an MMSE equalizer, a decision feedback equalizer, a maximum likelihood sequence estimator, or some other type of equalizer, all of which are known in the art. The equalization attempts to mitigate intersymbol interference due to frequency selectivity in the MISO channel. The matched filtering and equalization may be integrated together (e.g., matched filter 410 may be embedded in equalizer 412).

[0106] FIG. 4B shows a block diagram of an RX spatial processor 160b, which is another embodiment of RX spatial processor 160 in FIG. 1. RX spatial processor 160b

performs spectral despreading in the time domain and may be used in conjunction with TX spatial processor 130b in FIG. 3B. Within RX spatial processor 160b, matched filter 410 performs matched filtering of the received symbol stream $y_{miso}(n)$ with the matched filter $m_{miso}(n) = \underline{v}_{miso}^H \underline{f}^H(L-n)$ and provides the detected symbol stream $\tilde{s}_{miso}(n)$. A despreader 412 then despreads the detected symbol stream with (the complex conjugate of) the PN sequence used by transmitter 110 and provides the recovered symbol stream $\hat{s}_{miso}(n)$. The despreading may be performed with a rake receiver in similar manner as for a CDMA system, which is known in the art.

[0107] **FIG. 4C** shows a block diagram of an RX spatial processor 160c, which is yet another embodiment of RX spatial processor 160 in FIG. 1. RX spatial processor 160c performs OFDM demodulation and may be used in conjunction with TX spatial processor 130c in FIG. 3C. RX spatial processor 160c includes an OFDM demodulator 420, N_F matched filters 430a through 430f for the N_F subbands, and a multiplexer 432.

[0108] Within RX spatial processor 160c, OFDM demodulator 420 performs OFDM demodulation on the received symbol stream $y_{miso}(n)$. OFDM demodulator 420 first removes the cyclic prefix in each received OFDM symbol to obtain a received transformed symbol. OFDM demodulator 420 then transforms each received transformed symbol to the frequency domain using a fast Fourier transform (FFT) to obtain a set of N_F received symbols for the N_F subbands. OFDM demodulator 420 provides N_F received symbol substreams $y_{miso}(k)$, for $k=1, 2, \dots, N_F$, for the N_F subbands to N_F matched filters 430a through 430f. Each matched filter 430 performs matched filtering of its received symbol substream $y_{miso}(k)$ with its matched filter $m_{miso}(k) = \underline{v}_{miso}^H \underline{h}^H(k)$, which is a complex-valued scalar, and provides a detected symbol substream $\tilde{s}_{miso}(k)$. Multiplexer 432 receives and multiplexes the N_F detected symbol substreams from all N_F matched filters 430a through 430f and provides the recovered symbol stream $\hat{s}_{miso}(n)$. Fewer than N_F subbands may be used for data transmission. In this case, the received symbols for the unused subbands are discarded and the matched filtering is not performed for the unused subbands.

[0109] **FIG. 5** shows a block diagram of a receiver 150x, which is an embodiment of receiver 150 in FIG. 1. RX spatial processor 160 performs matched filtering and other

pre-processing on the received symbol stream $y_{miso}(n)$ and provides the recovered symbol stream $\hat{s}_{miso}(n)$ to RX data processor 170.

[0110] Within RX data processor 170, a symbol demapping unit 512 demodulates the recovered symbols in accordance with the modulation scheme used for the data stream, as indicated by a demodulation control provided by controller 180. A channel deinterleaver 514 then deinterleaves the demodulated data in a manner complementary to the interleaving performed at transmitter 110. If the interleaving is dependent on transmission mode, then controller 180 provides a deinterleaving control to channel deinterleaver 514. A decoder 516 then decodes the deinterleaved data in a manner complementary to the encoding performed at transmitter 110, as indicated by a decoding control provided by controller 180. For example, a turbo decoder or a Viterbi decoder may be used for decoder 516 if transmitter 110 performs turbo or convolutional coding, respectively. Decoder 516 may also provide the status of each received data packet (e.g., indicating whether the packet was received correctly or in error).

[0111] Channel estimator 172 obtains received pilot symbols from receiver unit 154, estimates the MISO channel response and the noise floor at receiver 150x based on the received pilot symbols, and provides the channel impulse response estimate $\hat{h}(n)$ and the noise floor estimate $\hat{\sigma}^2$ to controller 180. Controller 180 performs various functions related to eigensteering, matched filtering, and rate control for data transmission. For example, a matrix computation unit 522 within controller 180 performs computation to derive the frequency-independent steering vector \underline{v}_{miso} for transmitter 110 and the matched filter for receiver 150. Unit 522 may also estimate the received SNR of the data stream. A transmission mode selector 524 selects a suitable transmission mode for the data stream $d(n)$ based on the received SNR. Memory unit 182 may store a look-up table (LUT) 526 for all of the transmission modes supported by the MISO system and their required SNRs. Controller 180 provides the selected transmission mode for the data stream, the TX steering vector, acknowledgments (ACKs) and/or negative acknowledgments (NAKs), and so on as feedback information for transmitter 110.

4. MIMO System

- [0112] For a MIMO system, N_S spatial channels are available for data transmission, where $N_S \leq \min\{N_T, N_R\}$. One data stream may be transmitted on each spatial channel. Each data stream may be independently processed in accordance with a transmission mode selected for that data stream.
- [0113] **FIG. 6** shows a block diagram of a transmitter 610 and a receiver 650 in a MIMO system 600. At transmitter 610, a TX data processor 620 receives N_D data streams, where $N_S \geq N_D \geq 1$. TX data processor 620 codes, interleaves, and modulates each data stream in accordance with its selected transmission mode and provides a corresponding data symbol stream. A TX spatial processor 630 receives N_D data symbol streams from TX data processor 620, performs wideband processing (if any) and eigensteering based on a set of N_D or N_R TX steering vectors provided by controller 640, multiplexes in pilot, and provides N_T transmit chip streams for the N_T transmit antennas. The processing by TX data processor 620 and TX spatial processor 630 is described in further detail below. A transmitter unit 632 receives and conditions the N_T transmit chip streams to obtain N_T modulated signals, which are transmitted from N_T transmit antennas (not shown in FIG. 6) and via the MIMO channel to receiver 650.
- [0114] At receiver 650, the N_T transmitted signals are received by each of N_R receive antennas (not shown in FIG. 6), and the N_R received signals from the N_R receive antennas are provided to a receiver unit 654. Receiver unit 654 conditions, digitizes, and pre-processes each received signal to obtain a corresponding received symbol stream. Receiver unit 654 provides N_R received symbol streams to an RX spatial processor 660 and received pilot symbols to a channel estimator 672. RX spatial processor 660 performs matched filtering of the N_R received symbol streams with N_R matched filters and provides N_D recovered symbol streams, which are estimates of the N_D data symbol streams sent by transmitter 610. An RX data processor 670 then processes (e.g., demodulates, deinterleaves, and decodes) each recovered symbol stream in accordance with its transmission mode to obtain a decoded data stream, which is an estimate of the data stream sent by transmitter 610. RX data processor 670 may further provide the status of each received data packet.
- [0115] Channel estimator 672, matrix computation unit 674, and transmission mode selector 676 perform similar functions as channel estimator 172, matrix computation

unit 174, and transmission mode selector 176, respectively, in FIG. 1 to determine the N_D or N_R TX steering vectors for transmitter 610, the N_R matched filters for receiver 650, and the N_D transmission modes for the N_D data streams. A controller 680 assembles feedback information for transmitter 610, which may include the N_D or N_R TX steering vectors and the N_D transmission modes.

[0116] Controllers 640 and 680 direct the operation at transmitter 610 and receiver 650, respectively. Memory units 642 and 682 provide storage for program codes and data used by controllers 640 and 680, respectively. Memory units 642 and 682 may be internal to controllers 640 and 680, as shown in FIG. 6, or external to these controllers.

[0117] If $N_D = 1$, then the encoding, interleaving, and modulation for the single data stream may be performed as shown in FIG. 2. The eigensteering for the single data stream may be performed as shown in FIG. 3A, 3B, or 3C, depending on whether spectral spreading or OFDM modulation is performed on the data stream. However, the eigensteering is performed with the steering vector \underline{v}_{pm} for the principal mode or the steering vector \underline{v}_{mp} for the main path (instead of the steering vector \underline{v}_{miso}). The receiver matched filtering may be performed as described below. If $N_D > 1$, then the data processing (e.g., encoding, interleaving, and modulation) and the eigensteering may be performed as described below.

[0118] FIG. 7 shows a block diagram of an embodiment of TX data processor 620 in FIG. 6. For this embodiment, TX data processor 620 includes one set of encoder 712, channel interleaver 714, and symbol mapping unit 716 for each of the N_D data streams. Each set of encoder, channel interleaver, and symbol mapping unit receives and processes a respective data stream $d_i(n)$ in similar manner as described above for TX data processor 120 in FIG. 2 to obtain a corresponding data symbol stream $s_i(n)$. The coding, interleaving, and modulation for each data stream are performed based on the coding, interleaving, and modulation controls provided by controller 640, which are generated based on the transmission mode selected for that data stream.

[0119] FIG. 8A shows a block diagram of a TX spatial processor 630a, which is an embodiment of TX spatial processor 630 in FIG. 6 and may be used for multi-mode eigensteering. For this embodiment, TX spatial processor 630a includes N_D

eigensteering units 830a through 830d for the N_D data streams, a TX pilot processor 840, a combiner 850, and a multiplexer 860.

[0120] For multi-mode eigensteering, each eigensteering unit 830 receives a respective data symbol stream $s_\ell(n)$ and a respective frequency-independent steering vector $\underline{\mathbf{v}}_\ell$ in the matrix $\underline{\mathbf{V}}_{mm}$. Each eigensteering unit 830 performs eigensteering on its data symbol stream with its steering vector, as described above for FIG. 3A, and provides a respective set of N_T transmit symbol substreams $\underline{\mathbf{x}}_\ell(n)$ for the N_T transmit antennas. Eigensteering units 830a through 830d provide N_D sets of transmit symbol substreams for the N_D data streams. Combiner 850 includes N_T combiners 852a through 852t, one combiner 852 for each of the N_T transmit antennas. Each combiner 852 receives and combines a respective set of N_D transmit symbol substreams from eigensteering units 830a through 830d for its transmit antenna and provides a transmit symbol stream. Combiners 852a through 852t provide N_T transmit symbol streams $\underline{\mathbf{x}}_{mm}(n)$ for the N_T transmit antennas. Eigensteering units 830a through 830d and combiner 850 collectively perform the eigensteering shown in equation (28).

[0121] For receiver eigensteering, TX spatial processor 630a would include N_R eigensteering units 830, one for each of the N_R receive antennas. Each eigensteering unit 830 would receive a respective frequency-independent steering vector $\underline{\mathbf{v}}_{rx,i}$ in the matrix $\underline{\mathbf{V}}_{rx}$. If $N_D = 1$, then the same data symbol stream $s(n)$ is provided to all N_R eigensteering units and steered with the N_R steering vectors to obtain N_R sets of N_T transmit symbol substreams. Each combiner 852 would then receive and combine a respective set of N_R transmit symbol substreams from the N_R eigensteering units for its transmit antenna and provides a transmit symbol stream. If $N_D > 1$, then each data symbol stream may be provided to one or more of the N_R eigensteering units for the one or more receive antennas to which the data symbol stream is steered. The eigensteering is then performed in similar manner to obtain the N_T transmit symbol streams $\underline{\mathbf{x}}_{rx}(n)$ for the N_T transmit antennas.

[0122] TX pilot processor 840 receives and covers the pilot symbol with N_T orthogonal sequences, as described above for FIG. 3A, and provides N_T sequences of covered pilot symbols for the N_T transmit antennas. Multiplexer 860 includes N_T multiplexers 862a through 862t, one multiplexer 862 for each of the N_T transmit antennas. Each

multiplexer 862 receives and multiplexes the transmit symbols from an associated combiner 852 with the covered pilot symbols from an associated multiplier 842 and provides a respective stream of transmit chips. Multiplexers 862a through 862t provide N_T transmit chip streams $\underline{c}_{mimo}(n) = [c_1(n) \ c_2(n) \ \dots \ c_{N_T}(n)]^T$ for the N_T transmit antennas.

[0123] **FIG. 8B** shows a block diagram of a TX spatial processor 630b, which is another embodiment of TX spatial processor 630 in FIG. 6. TX spatial processor 630b performs spectral spreading in the time domain and includes N_D spreaders 810a through 810d for N_D data streams, N_D eigensteering units 830a through 830d, TX pilot processor 840, combiner 850, and multiplexer 860. Each spreader 810 receives and spectrally spreads a respective data symbol stream $s_i(n)$ with a PN spreading sequence and provides a corresponding stream of spread data symbols. The same or different PN sequences may be used for the N_D data symbol streams. Spreaders 810a through 810d provide N_D spread data symbol streams for the N_D data symbol streams. Eigensteering is then performed on each of the N_D spread data symbol streams (instead of the data symbol streams), in similar manner as described above for FIGS. 3A and 8A, to obtain N_T transmit chip streams for the N_T transmit antennas.

[0124] **FIG. 8C** shows a block diagram of a TX spatial processor 630c, which is yet another embodiment of TX spatial processor 630 in FIG. 6. TX spatial processor 630c performs OFDM modulation and includes N_D OFDM modulators 820a through 820d for N_D data streams, N_D eigensteering units 830a through 830d, TX pilot processor 840, combiner 850, and multiplexer 860.

[0125] Each OFDM modulator 820 performs OFDM modulation on a respective data symbol stream $s_i(n)$, in similar manner as described above for FIG. 3C, and provides a stream of data chips. OFDM modulators 820a through 820d provide N_D data chip streams for the N_D data streams. Eigensteering is then performed on each of the N_D data chip streams (instead of the data symbol stream), as described above for FIGS. 3A and 8A, to obtain N_T transmit chip streams for the N_T transmit antennas. Alternatively, the eigensteering may be performed in the frequency domain on the data symbol substream for each subband. In this case, each eigensteering unit uses the same steering vector \underline{v}_i for all subbands.

[0126] **FIG. 9A** shows a block diagram of an RX spatial processor 660a, which may be used for the case in which a single data stream is transmitted (i.e., $N_D = 1$). Each of N_R

receive antennas 652a through 652r receives the N_T transmitted signals from transmitter 610 and provides a received signal to an associated receiver unit 654. Each receiver unit 654 conditions, digitizes, and pre-processes its received signal and provides a received symbol stream $y_i(n)$.

[0127] RX spatial processor 660a includes N_R matched filters 910a through 910r for the N_R receive antennas, a combiner 912, and an equalizer 914. Each matched filter 910 performs matched filtering of its received symbol stream $y_i(n)$ with a matched filter $m_i(n) = \underline{\mathbf{v}}_{mimo}^H \underline{\mathbf{f}}_i^H (L - n)$ and provides a filtered symbol stream. The vector $\underline{\mathbf{v}}_{mimo}$ is equal to the steering vector $\underline{\mathbf{v}}_{pm}$ for principal mode eigensteering, the steering vector $\underline{\mathbf{v}}_{mp}$ for main path eigensteering, or the steering vector $\underline{\mathbf{v}}_{rx,i}$ for receiver eigensteering. For receiver eigensteering, each matched filter 910 is associated with a different steering vector $\underline{\mathbf{v}}_{rx,i}$ for its receive antenna, which is not shown in FIG. 9A. The vector $\underline{\mathbf{f}}_i(n)$ is the channel impulse response between the N_T transmit antennas and receive antenna i . Combiner 912 receives and combines the N_R filtered symbol streams from matched filters 910a through 910r and provides a detected symbol stream $\tilde{\mathbf{s}}_{mimo}(n)$. Equalizer 914 performs equalization on the detected symbol stream and provides the recovered symbol stream $\hat{\mathbf{s}}_{mimo}(n)$. Equalizer 914 may implement an MMSE equalizer, a decision feedback equalizer, a maximum likelihood sequence estimator, or some other type of equalizer.

[0128] FIG. 9B shows a block diagram of an RX spatial processor 660b, which may also be used for the case in which a single data stream is transmitted (i.e., $N_D = 1$). RX spatial processor 660b performs spectral despreading in the time domain and may be used in conjunction with TX spatial processor 630b in FIG. 8B.

[0129] RX spatial processor 660b includes N_R matched filters 910a through 910r for the N_R receive antennas, combiner 912, and a despreader 916. Each matched filter 910 performs matched filtering of a respective received symbol stream $y_i(n)$ with its matched filter $m_i(n) = \underline{\mathbf{v}}_{mimo}^H \underline{\mathbf{f}}_i^H (L - n)$ and provides a filtered symbol stream. Combiner 912 receives and combines the N_R filtered symbol streams and provides the detected symbol stream $\tilde{\mathbf{s}}_{mimo}(n)$. Despreader 916 then despreads the detected symbol stream

with the PN sequence used by transmitter 610 and provides the recovered symbol stream $\hat{s}_{mimo}(n)$.

[0130] FIG. 9C shows a block diagram of an RX spatial processor 660c, which may also be used for the case in which a single data stream is transmitted (i.e., $N_D = 1$). RX spatial processor 660c performs OFDM demodulation and may be used in conjunction with TX spatial processor 630c in FIG. 8C.

[0131] RX spatial processor 660c includes N_R antenna matched filters 920a through 920r for the N_R receive antennas, N_F combiners 932a through 932f for the N_F subbands, and a multiplexer 934. Each antenna matched filter 920 performs matched filtering for one receive antenna and includes an OFDM demodulator 922 and N_F matched filters 930a through 930f for the N_F subbands.

[0132] Within each antenna matched filter 920, OFDM demodulator 922 performs OFDM demodulation on the received symbol stream $y_i(n)$ for the associated receive antenna and provides N_F received symbol substreams $y_i(k)$, for $k = 1, 2, \dots, N_F$, for the N_F subbands to N_F matched filters 930a through 930f. Each matched filter 930 performs matched filtering of its received symbol substream $y_i(k)$ with its matched filter $m_i(k) = \mathbf{v}_{mimo}^H \mathbf{h}_i^H(k)$ and provides a filtered symbol substream. The vector $\mathbf{h}_i(k)$ is the channel frequency response for receive antenna i for subband k . Matched filters 930a through 930f for each antenna matched filter 920 provide N_F filtered symbol substreams for the N_F subbands to N_F combiners 932a through 932f.

[0133] Each combiner 932 receives and combines the N_R filtered symbol substreams from N_R antenna matched filters 920a through 920r for its subband and provides a detected symbol substream for the subband. Multiplexer 934 receives and multiplexes the N_F detected symbol substreams from combiners 932a through 932f for the N_F subbands and provides the recovered symbol stream $\hat{s}_{mimo}(n)$.

[0134] FIG. 9D shows a block diagram of an RX spatial processor 660d, which may be used for multi-mode eigensteering with $N_D > 1$. RX spatial processor 660d may be used in conjunction with TX spatial processor 630a in FIG. 8A or TX spatial processor 630b in FIG. 8B.

[0135] RX spatial processor 660d includes N_R matched filters 940a through 940r for the N_R receive antennas, N_D combiners 942a through 942d for the N_D data streams, a space-

time equalizer 944, and N_D despreaders 946a through 946d for the N_D data streams. Each matched filter 940 performs matched filtering of a respective received symbol stream $y_i(n)$ with a matched filter $\underline{m}_i(k) = \underline{\mathbf{V}}_{mm}^H \underline{h}_i^H(L-n)$ for an associated receive antenna and provides N_D filtered symbol substreams for the N_D data symbol streams. The matrix $\underline{\mathbf{V}}_{mm}$ includes N_D steering vectors $\underline{\mathbf{v}}_\ell$, for $\ell = 1, 2, \dots, N_D$, for the N_D data symbol streams. Each matched filter 940 thus performs matched filtering of the received symbol stream $y_i(n)$ with N_D matched filters $m_{i,\ell}(n) = \underline{\mathbf{v}}_\ell^H \underline{h}_i^H(L-n)$, for $\ell = 1, 2, \dots, N_D$, where $\underline{\mathbf{v}}_\ell$ is the ℓ -th column of $\underline{\mathbf{V}}_{mm}$, to obtain the N_D filtered symbol substreams for the associated receive antenna.

[0136] Each combiner 942 receives and combines the N_R filtered symbol substreams from matched filters 940a through 940r for one data symbol stream and provides the detected symbol stream $\tilde{z}_i(n)$ for the data stream. Matched filters 940a through 940r and combiners 942a through 942d collectively perform the matched filtering shown in equation (29) and provides N_D detected symbol streams $\underline{\tilde{z}}(n)$ for the N_D data symbol streams.

[0137] If multiple data symbol streams are transmitted, then there is likely to be cross-talk between these data symbol streams at receiver 650. Space-time equalizer 944 performs equalization on the N_D detected symbol streams from combiners 942a through 942d and provides N_D equalized symbol streams. Space-time equalizer 944 may implement an MMSE linear equalizer, a decision feedback equalizer, a maximum likelihood sequence estimator, or some other type of equalizer that can jointly operate on multiple streams to mitigate cross-talk and/or maximize the received SNR in the presence of cross-talk, intersymbol interference, and noise. Space-time equalizer 944 may also implement the successive equalization and interference cancellation processing technique. Space-time equalizer 944 may also be omitted.

[0138] If spreading is not performed at transmitter 610, as shown in FIG. 8A, then the N_D equalized symbol streams from space-time equalizer 944 are provided as the N_D recovered symbol streams $\hat{\underline{z}}(n)$. If spreading is performed at transmitter 610 for each data symbol stream, as shown in FIG. 8B, then each despreader 946 receives and despreads a respective equalized symbol stream with the PN sequence and provides a

corresponding recovered symbol stream. Despanders 946a through 946d would then provide the N_D recovered symbol streams $\hat{\underline{s}}(n)$.

[0139] **FIG. 9E** shows a block diagram of an RX spatial processor 660e, which may be used for receiver eigensteering with $N_D > 1$. RX spatial processor 660e includes N_R matched filters 950a through 950r for the N_R receive antennas, a combiner 952, a space-time equalizer 954, and N_D despanders 956a through 956d for the N_D data symbol streams. Each matched filter 950 performs matched filtering of a respective received symbol stream $y_i(n)$ with a matched filter $\underline{m}_{rx,i}(k) = \underline{v}_{rx,i}^H \underline{f}_i^H(L-n)$ for an associated receive antenna and provides a filtered symbol stream. Combiner 952 receives the N_R filtered symbol streams from matched filters 950a through 950r, combines the filtered symbol streams for all receive antennas used for each data symbol stream, and provides the detected symbol stream $\tilde{z}_i(n)$ for that data symbol stream. The combining is dependent on the eigensteering performed at the transmitter (i.e., the specific receive antennas to which each data symbol stream is steered). Combiner 952 provides N_D detected symbol streams $\tilde{\underline{z}}(n)$ for the N_D data symbol streams. Space-time equalizer 954 and despanders 956a through 956d operate on the N_D detected symbol streams as described above for FIG. 9D and provide the N_D recovered symbol streams $\hat{\underline{s}}(n)$.

[0140] **FIG. 9F** shows a block diagram of an RX spatial processor 660f, which may also be used for multi-mode eigensteering with $N_D > 1$. RX spatial processor 660f performs OFDM demodulation and may be used in conjunction with TX spatial processor 630c in FIG. 8C.

[0141] RX spatial processor 660f includes N_R antenna matched filters 970a through 970r for the N_R receive antennas, N_F combiners 982a through 982f for the N_F subbands, N_F space-time equalizers 984a through 984f for the N_F subbands, and a multiplexer 986. Each antenna matched filter 970 performs matched filtering for one receive antenna and includes an OFDM demodulator 972 and N_F matched filters 980a through 980f for the N_F subbands.

[0142] Within each antenna matched filter 970, OFDM demodulator 972 performs OFDM demodulation on the received symbol stream $y_i(n)$ for the associated antenna and provides N_F received symbol substreams $y_i(k)$, for $k = 1, 2, \dots, N_F$, for the N_F subbands to N_F matched filters 980a through 980f. Each matched filter 980 performs

matched filtering of its received symbol substream $y_i(k)$ with its matched filter $\underline{\mathbf{m}}_i(k) = \underline{\mathbf{V}}_{mm}^H \underline{\mathbf{h}}_i^H(k)$ and provides N_D filtered symbol substreams for the N_D data symbol streams for its subband. Matched filters 980a through 980f for each antenna matched filter 970 provide N_F sets of N_D filtered symbol substreams for the N_F subbands to N_F combiners 982a through 982f.

[0143] Each combiner 982 receives and combines the N_R sets of N_D filtered symbol substreams from N_R antenna matched filters 970a through 970r for its subband and provides N_D detected symbol substreams for its subband. Although not shown in FIG. 9F, each combiner 982 includes N_D summers, one summer for each data symbol stream. Each summer receives and sums the N_R filtered symbol substreams from antenna matched filters 970a through 970r for its subband and its data symbol stream to obtain the detected symbol substream for its subband.

[0144] Each spatial equalizer 984 performs equalization on the N_D detected symbol substreams from an associated combiner 982 for its subband and provides N_D equalized symbol streams for the subband. Spatial equalizer 984 may implement an MMSE linear equalizer or some other equalizer that jointly operates on multiple symbol streams to mitigate cross-talk and/or maximize the received SNR. Spatial equalizer 984 may also implement the successive equalization and interference cancellation processing technique.

[0145] Multiplexer 986 receives N_F sets of N_D equalized symbol substreams from combiners 984a through 984f for the N_F subbands. Multiplexer 986 then multiplexes the N_F equalized symbol substreams from combiners 984a through 984f for each data symbol stream and provides the recovered symbol stream $\hat{s}_\ell(n)$ for that data symbol stream.

[0146] FIG. 10 shows a block diagram of a receiver 650x, which is an embodiment of receiver 650 in FIG. 6. RX spatial processor 660 performs matched filtering and post-processing on the N_R received symbol streams $y_i(n)$, for $i = 1, 2, \dots, N_R$, and provides N_D recovered symbol streams $\hat{s}_\ell(n)$, for $\ell = 1, 2, \dots, N_D$, to RX data processor 670. RX data processor 670 includes one set of symbol demapping unit 1012, deinterleaver 1014, and decoder 1016 for each of the N_D recovered symbol streams. Each set of symbol demapping unit, deinterleaver, and decoder processes a respective recovered symbol

stream as described above for FIG. 5. RX data processor 670 provides N_D decoded data streams $\hat{d}_\ell(n)$, for $\ell = 1, 2, \dots, N_D$.

[0147] Channel estimator 672 estimates the channel response and the receiver noise floor based on the received pilot symbols from receiver units 654a through 654r and provides the channel impulse response estimate $\hat{\underline{H}}(n)$ and the noise floor estimate $\hat{\sigma}^2$ to controller 680. Controller 680 performs various functions related to eigensteering, matched filtering, and rate control for the data transmission. For example, a matrix computation unit 1022 may perform computation to derive (1) the steering vector \underline{v}_{pm} for principal mode eigensteering, (2) the steering vector \underline{v}_{mp} for main path eigensteering, (3) N_D steering vectors \underline{v}_ℓ , for $\ell = 1, 2, \dots, N_D$, for multi-mode eigensteering, or (4) N_R steering vectors $\underline{v}_{rx,i}$, for $i = 1, 2, \dots, N_R$, for receiver eigensteering. Computation unit 1022 also derives N_R matched filters for receiver 650 and may further estimate the received SNR of the N_D data streams. A transmission mode selector 1024 selects a suitable transmission mode for each data stream based on its received SNR. Memory unit 682 may store a look-up table 1026 for all of the supported transmission modes and their required SNRs. Controller 680 provides the N_D TX steering vectors, the N_D selected transmission modes for the N_D data streams, ACKs and/or NAKs, and so on as feedback information for transmitter 610.

[0148] For embodiments described above, the receiver estimates the channel response of the MISO or MIMO channel, derives the steering vector(s) for the transmitter and the matched filter(s) for the receiver, and sends back the steering vector(s) as feedback information. For other embodiments, it may be possible for the transmitter to estimate the channel response and derive the steering vector(s). For example, in a time division duplexed (TDD) system with a shared frequency band, the downlink and uplink channel responses may be assumed to be reciprocal of one another. That is, if $\underline{H}(k)$ represents a channel frequency response matrix from antenna array A to antenna array B for subband k , then a reciprocal channel implies that the coupling from array B to array A is given by $\underline{H}^T(k)$. For the TDD system, the reciprocal channel characteristics can be exploited to allow the transmitter to estimate the link observed by the receiver based on pilot sent by the receiver on the other link. In general, the channel estimation and the

computation of the steering vectors may be performed by the receiver or the transmitter, depending on the system design.

[0149] **FIG. 11** shows a flow diagram of an embodiment of a process 1100 for performing principal mode eigensteering, multi-mode eigensteering, and main path eigensteering in a MIMO system. Initially, a plurality of channel response matrices are obtained for the channel response of the MIMO channel in the MIMO system (at block 1112). These channel response matrices may be (1) $L+1$ channel impulse response matrices for $L+1$ time delays (i.e., $\underline{H}(n)$ for $n=0, 1, \dots, L$) or (2) N_F channel frequency response matrices for N_F subbands (i.e., $\underline{H}(k)$ for $k=1, 2, \dots, N_F$).

[0150] A single correlation matrix is computed for the MIMO channel based on the channel response matrices (at block 1114). For principal mode eigensteering and multi-mode eigensteering, the single correlation matrix may be obtained by (1) computing a correlation matrix of each of the plurality of channel response matrices and (2) summing the correlation matrices for the channel response matrices to obtain the single correlation matrix, as shown in equation (18). For main path eigensteering, the single correlation matrix may be obtained by (1) determining the energy of each of the channel impulse response matrices, (2) identifying the channel impulse response matrix with the highest energy, (3) computing a correlation matrix of the channel impulse response matrix with the highest energy, and (4) defining the single correlation matrix for the MIMO channel as the correlation matrix of the channel impulse response matrix with the highest energy, as shown in equations (33) and (34) and the related description.

[0151] The single correlation matrix is then decomposed (e.g., using eigenvalue decomposition) to obtain N_D steering vectors for N_D spatial channels of the MIMO channel, where $N_S \geq N_D \geq 1$ and N_S is the number of eigenmodes of the single correlation matrix (at block 1116). For principal mode eigensteering and main path eigensteering, $N_D=1$ and only one steering vector is obtained. For multi-mode eigensteering, $N_D > 1$ and multiple steering vectors are obtained.

[0152] The operations shown at blocks 1112, 1114, and 1116 may be performed by receiver 650 in FIG. 6. The operations shown at blocks 1112, 1114, and 1116 may also be performed by transmitter 610 for a time-division duplexed (TDD) system in which the downlink and uplink share the same frequency band. In any case, the N_D steering

vectors may be used for eigensteering by the transmitter and matched filtering by the receiver.

[0153] At the transmitter, each steering vector may be used for frequency-independent eigensteering or spatial processing of a data stream sent on the spatial channel associated with the steering vector (at block 1122). The transmitter performs eigensteering on N_D data symbol streams with the N_D steering vectors to generate N_T transmit symbol streams (at block 1124), which are further processed and transmitted from the N_T transmit antennas (at block 1126).

[0154] At the receiver, matched filtering of N_R received symbol streams for N_R receive antennas, where $N_R \geq N_D$, may be performed in either the time domain or frequency domain. A matched filter may be derived for each receive antenna based on the N_D steering vectors and a plurality of channel response vectors for that receive antenna (at block 1132). The channel response vectors for each receive antenna may be obtained from the channel response matrices. The received symbol stream for each receive antenna is filtered with the matched filter for that receive antenna to obtain N_D filtered symbol substreams, one substream for each steering vector used by the transmitter (at block 1134). The filtered symbol substreams from all N_R matched filters for the N_R receive antennas are then combined to obtain N_D detected symbol streams for the N_D data streams sent by the transmitter (at block 1136). Equalization may be performed on the N_D detected symbol streams to obtain N_D recovered symbol streams (at block 1138). If $N_D > 1$, then space-time equalization (e.g., with an MMSE-LE, a DFE, or an MLSE) may be performed on the multiple detected symbol streams to obtain multiple recovered symbol streams.

[0155] FIG. 12 shows a flow diagram of an embodiment of a process 1200 for performing receiver eigensteering in a MISO or MIMO system with N_T transmit antennas and N_R receive antennas, where $N_T > 1$ and $N_R \geq 1$ in this case. Initially, N_R sets of channel response vectors are obtained for the N_R receive antennas, one set for each receive antenna (at block 1212). Each set of channel response vectors is indicative of the channel frequency response or the channel impulse response between the N_T transmit antennas and one receive antenna.

[0156] A single correlation matrix is computed for each receive antenna based on the set of channel response vectors for that receive antenna (at block 1214). This may be

achieved by (1) computing a correlation matrix of each of the channel response vectors for the receive antenna and (2) summing correlation matrices for the channel response vectors for the receive antenna to obtain the single correlation matrix for the receive antenna. The single correlation matrix for each receive antenna is then decomposed (e.g., using eigenvalue decomposition) to obtain a steering vector for the receive antenna (at block 1216). The operations shown at blocks 1212, 1214, and 1216 may be performed by receiver 150 in FIG. 1 or receiver 650 in FIG. 6. The operations shown at blocks 1212, 1214, and 1216 may also be performed by transmitter 110 in FIG. 1 or transmitter 610 in FIG. 6 for a TDD system. In any case, N_R steering vectors are obtained for the N_R receive antennas and may be used for spatial processing by the transmitter and matched filtering by the receiver.

[0157] At the transmitter, the N_R steering vectors may be used for frequency-independent eigensteering or spatial processing of N_D data streams, where $N_R \geq N_D \geq 1$ and $N_T \geq N_D$ (at block 1222). For a MISO system with only one receive antenna ($N_R = 1$), one data stream is sent using one steering vector obtained for the one receive antenna (at blocks 1224 and 1226). For a MIMO system with a plurality of receive antennas ($N_R > 1$), one or multiple data streams may be sent using the N_R steering vectors obtained for the N_R receive antennas. Each data stream may be steered toward one or multiple receive antennas.

[0158] At the receiver, matched filtering of N_R received symbol streams for the N_R receive antennas may be performed in either the time domain or the frequency domain. A matched filter is derived for each receive antenna based on the steering vector and the set of channel response vectors for that receive antenna (at block 1232). The received symbol stream for each receive antenna is filtered with the matched filter for that receive antenna to obtain a filtered symbol stream for the receive antenna (at block 1234). The N_R filtered symbol streams from the N_R matched filters for the N_R receive antennas are then combined to obtain N_D detected symbol streams for the N_D data streams sent by the transmitter (at block 1236). Equalization may be performed on the N_D detected symbol streams to obtain N_D recovered symbol streams for the N_D data streams sent by the transmitter (at block 1238).

5. Rate Selection

[0159] For both MISO system 100 and MIMO system 600, the receiver may estimate the received SNR for each spatial channel. The SNR computation may be dependent on the eigensteering scheme used for data transmission, as described above. The receiver may then compute an operating SNR, $\gamma_{op}(\ell)$, for each spatial channel based on the received SNR, $\gamma_{rx}(\ell)$, and an SNR offset, $\gamma_{os}(\ell)$, for the spatial channel (e.g., $\gamma_{op}(\ell) = \gamma_{rx}(\ell) + \gamma_{os}(\ell)$, where the units are in dB). The SNR offset may be used to account for estimation error, variability in the channel, and other factors. The receiver may select a suitable transmission mode for each spatial channel based on the operating SNR for that spatial channel.

[0160] The system may be designed to support a set of transmission modes. One of the supported transmission modes may be for a null rate (i.e., a data rate of zero). Each of the remaining transmission modes is associated with a particular non-zero data rate, a particular coding scheme or code rate, a particular modulation scheme, and a particular minimum SNR required to achieve the desired level of performance (e.g., 1% packet error rate (PER)) for a non-fading AWGN channel. For each supported transmission mode with a non-zero data rate, the required SNR is obtained based on the specific system design (i.e., the particular code rate, interleaving scheme, modulation scheme, and so on, used by the system for that transmission mode) and for an AWGN channel. The required SNR may be obtained by computer simulation, empirical measurements, and so on, as is known in the art. The set of supported transmission modes and their required SNRs may be stored in a look-up table.

[0161] The operating SNR, $\gamma_{op}(\ell)$, for each spatial channel may be provided to the look-up table, which then provides the transmission mode $q(\ell)$ for that spatial channel. This transmission mode $q(\ell)$ is the supported transmission mode with the highest data rate and a required SNR, $\gamma_{req}(\ell)$, that is less than or equal to the operating SNR (i.e., $\gamma_{req}(\ell) \leq \gamma_{op}(\ell)$). The receiver thus selects the highest possible data rate for each spatial channel based on the operating SNR for that spatial channel.

[0162] For clarity, specific embodiments of various eigensteering schemes have been described above. Other variants of these eigensteering schemes may also be devised, and this is within the scope of the invention. For example, the single correlation matrix

for the MIMO channel may be computed in other manners than that described above for the principal mode and multi-mode eigensteering schemes. As another example, multiple data symbol streams may be transmitted on multiple spatial channels of the main path. As yet another example, N_D data symbol streams may be transmitted on the N_D best spatial channels based on the energy of the spatial channels. Other eigensteering schemes may also be devised based on the teachings provided herein, and this is within the scope of the invention.

[0163] The eigensteering techniques described herein may be implemented by various means. For example, these techniques may be implemented in hardware, software, or a combination thereof. For a hardware implementation, the processing at the transmitter for eigensteering and other pertinent functions may be implemented within one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), digital signal processing devices (DSPDs), programmable logic devices (PLDs), field programmable gate arrays (FPGAs), processors, controllers, micro-controllers, microprocessors, other electronic units designed to perform the functions described herein, or a combination thereof. The processing at the receiver for matched filtering and other pertinent functions may also be implemented within one or more ASICs, DSPs, and so on.

[0164] For a software implementation, the eigensteering techniques may be implemented with modules (e.g., procedures, functions, and so on) that perform the functions described herein. The software codes may be stored in memory units (e.g., memory units 142 and 182 in FIG. 1 or memory units 642 and 682 in FIG. 6) and executed by a processor (e.g., controllers 140 and 180 in FIG. 1 or controller 640 and 680 in FIG. 6). The memory unit may be implemented within the processor or external to the processor, in which case it can be communicatively coupled to the processor via various means as is known in the art.

[0165] Headings are included herein for reference and to aid in locating certain sections. These headings are not intended to limit the scope of the concepts described therein under, and these concepts may have applicability in other sections throughout the entire specification.

[0166] The previous description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic

principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

WHAT IS CLAIMED IS: